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J952-22

Synthetic Fuels for Transportation

Background Paper #1

The Future Potential of Electric and Hybrid Vehicles

January 1982

Prepared under contract by
W.M. Carriere, W.F. Hamilton, and L.M. Morecraft
of the General Research Corp.

OTA Background Papers are documents that contain information believed to be useful to various parties. The information undergirds formal OTA assessments or is an outcome of internal exploratory planning and evaluation. The material is usually not of immediate policy interest such as is contained in an OTA Report or Technical Memorandum, nor does it present options for Congress to consider.

CONGRESS OF THE UNITED STATES
Office of Technology Assessment
Washington, D.C. 20510

Contractor Acknowledgment

This background paper was prepared for the Office of Technology Assessment as background information for its study, "Synthetic Fuels for Transportation." Much of the analysis on which this report is based was performed for the Department of Energy (DOE) by the General Research Corp. under the technical direction of Dr. Daniel P. Maxfield, Analysis and Assessment Branch, Office of Transportation Programs, DOE. Special thanks are due Dr. Maxfield for his cooperation and support in the preparation of this report.

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Preface

The Office of Technology Assessment (OTA), at the request of the Senate Committee on Commerce, Science, and Transportation, initiated a comparative study of automobile fuel efficiency and the technology of alternative energy sources. The assessment, "Synthetic Fuels for Transportation," will be completed in early 1982. Included in that analysis are the assessment of automobile engines, other vehicle systems, and electric and hybrid vehicles.

This contractor report was prepared by the General Research Corp., under the direction of Dr. D. P. Maxfield, as technical input to the OTA study. It deals with electric and hybrid vehicle systems and their possible benefits and impacts.

OTA does not necessarily agree or disagree with the contents of this contractor report, but feels that the material will be helpful to those who are interested in the detailed issues of electrification of transportation.

John H. Gibbons

JOHN H. GIBBONS
Director

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1 SUMMARY

In the electric vehicle, an electric motor replaces the conventional gasoline engine, and a storage battery replaces the gasoline tank. The battery may be recharged from a standard electrical outlet, thus making the vehicle independent of the gasoline pump. It is this prospect which has primarily motivated widespread public interest, a government program of development and demonstration, and a project at General Motors to market mass-produced electric cars in 1985.

For the first time since the early 1900s, many expect electric vehicles to enter the US automotive market in substantial numbers. Yet their prospects are far from obvious. The degree to which new technology will improve the performance and cost of electric vehicles is uncertain. Sales of electric vehicles are difficult to forecast and may be insufficient to displace many gasoline-powered vehicles. Electric utilities may generate recharge electricity in oil-fired power stations, in part offsetting reductions in gasoline use for vehicular fuel. Overall, electric vehicles may not compare favorably with competing alternatives such as much-improved conventional vehicles and synthetic fuels.

In the past, electric vehicles generally have not been competitive with gasoline-powered vehicles because they have been expensive and restricted in driving range. This has been primarily due to the weight, cost, and limitations of the electric storage battery. Batteries available during the 1970s may be accurately likened to a gasoline tank for a subcompact car costing over $1,000, weighing over 1,000 pounds, requiring replacement every 10,000 miles, and holding only 2 gallons. This sort of fuel storage limits driving range to about 40 miles and adds depreciation costs of 10 cents per mile to operating expenses. Furthermore, refueling in a few minutes at any convenient service station is not possible. Instead, recharging a storage battery usually requires 8 to 12 hours.

Major technological advances, however, appear imminent. In the near term (before 1990), electric cars with useful ranges of 100 miles may become available. Purchase prices, however, will probably exceed those of comparable conventional cars by up to 75 percent, largely because of the weight, bulk, and cost of the required batteries. Overall life-cycle costs will also exceed those of conventional cars, by perhaps as much as 25 percent. Despite improved battery life, battery depreciation will remain high enough to offset savings expected from low maintenance costs and low electricity costs. There is a possibility, however, that advanced battery technology which might come in the 1990s could bring 150-mile ranges, initial prices only a third higher than those of comparable conventional cars, and life-cycle costs which are actually lower, even with electricity and gasoline prices (in constant dollars) no higher than those of 1980.

Though improvements in electric motors and controllers were assumed for these projections, the critical assumptions are longer life and higher energy content of future batteries. Near-term batteries which may be successfully mass-produced before 1990 include lead-acid, nickel-iron, nickel-zinc, and zinc-chlorine systems with 2 to 3 times more energy storage per pound than batteries available during the 1970s, and operating lifetimes as much as 4 times longer. It is uncertain which of these near-term candidates will succeed, however, and it is not guaranteed that any will achieve the performance and life projected here. More advanced batteries for the 1990s, such as improved zinc-chlorine systems or high-temperature lithium-metal sulfide batteries, may be able to store 4 to 6 times the energy per pound of 1970s batteries, and last for the useful life of the vehicle. When and if such advanced batteries will be successfully developed is very uncertain.

A 100-mile range for the electric car is not only a reasonable prospect for the later 1980s, it is also a goal which has been stated by both the US Department of Energy and General Motors. Though enough for most urban travel, it would probably suffice for only about 80 percent of the total annual mileage driven by typical US cars, which are used for long-distance travel as well as urban travel. The remaining 20 percent would be shifted to another conventional car. Thus, the electric car which replaces the typical conventional car will probably displace only about 80 percent of its annual petroleum use (even if no petroleum is used to generate recharge energy).

In multi-car households, trips beyond the capability of an electric car could usually be shifted to a conventional car with little inconvenience. Inadequacy for some 20 percent of typical travel, however, indicates that even the 100-mile range between recharges would be an important limitation to many motorists. The hybrid-electric car relieves this limitation by including an internal-combustion engine as well as an electric motor and storage battery for propulsion. Electricity alone would be used for driving within the speed and range capability of the electric motor and battery. For more demanding driving, the engine could be started to provide power, endurance, and quick refueling capability like that of the conventional car.

The simplest hybrid of this sort would utilize the internal combustion engine only for extending range beyond that possible using electricity alone. The necessary engine would be quite small (15-25 horsepower, just adequate for freeway cruising at speeds up to 55 mph), and it would be started only after battery depletion during long trips. In most urban driving the engine would not be operated at all. The range-extension hybrid would thus provide most of the benefits of the pure electric vehicle, yet impose no range limitation or sacrifice of mobility. Furthermore, it could be little or no more expensive than the pure electric vehicle, because the weight and cost of the engine could be offset by reductions in the weight and cost of the required battery.

Petroleum saving of the range-extension hybrid would be about the same as that of the 100-mile electric car. That is, substitution of the hybrid for a conventional car would reduce petroleum consumption by 80 percent (assuming no use of petroleum for generating recharge electricity). Though its range on electricity alone would be less than that of the all-electric vehicle, this range could be utilized on every trip, including part of long trips which pure electric cars could not make.

The acceleration capability of electric (and range-extension hybrid) vehicles will be low, like that of many diesel cars, but nonetheless adequate to keep up with traffic in city streets and on freeways. US motorists have often preferred higher acceleration, however, and this can be provided by a high-performance hybrid design. In this hybrid, slow driving would be accomplished without use of the internal-combustion engine. At the driver's demand for high acceleration or high speed, however, the engine would be started instantly to add the necessary extra power. An engine several times larger than that of a range-extension hybrid is required by the high-performance hybrid to achieve the acceleration and speed capabilities of recent full-size US sedans. Typically, however, the weight and cost of the larger engine are more than offset by reductions in the size of the associated electric motor and battery. It is estimated that the initial prices for high-performance hybrids would be intermediate between the prices of conventional cars and all-electric cars.

The reduced capability of the electric drive, however, necessitates more extensive use of the internal-combustion engine in the high-performance hybrid. As a result, the annual petroleum consumption of such a hybrid is estimated at 30 to 60 percent that of a comparable conventional car. In addition, the on-off mode of internal-combustion engine operation also leads to technical problems and risks associated with cold starts, engine longevity, and smooth driveability. Though government development efforts are focused on the high-performance hybrid, the range-extension hybrid entails substantially less technical difficulty and risk, while offering the potential for substantially greater petroleum saving.

Hybrids are generally expected to enter the marketplace several years after electric vehicles. Pure electric vehicles are simpler and less risky to develop. Moreover, hybrids cannot be successfully developed until satisfactory electric drive components and storage batteries have been developed. Though high battery energy is less important for hybrids, long battery life remains critical. Without it, costs of battery depreciation will be so high for either hybrid or electric vehicles that wide market acceptance is unlikely.

The electric utility industry and electric outlets in garages constitute the key elements of the infrastructure required for operating electric vehicles. So long as recharging is done late at night, existing power plants and power lines are generally adequate, though addition of higher-capacity outlets specifically for battery recharging would be desirable in many garages.

Electric generating capacity already existing and planned in the US could recharge tens of millions of electric vehicles each night. The reason for this is that at present, demand for electricity late at night is ordinarily much less than during the peak hour of the day, which usually occurs in the late afternoon. In 1979, US electric utilities operated at an average power output equal to only 64 percent of their maximum power output during the year. If 25 percent of all cars and light trucks in the United States had been electric, recharging would have increased average utility power output to only 68 percent of the maximum achieved during the year. Given recharging late at night, this increase could have been readily accommodated.

At present, few utilities have rate structures or metering and control equipment to encourage recharging late at night. Many utilities are moving towards peak and off-peak pricing, however, which would provide substantially lower electricity prices for late night recharging. Utilities are also moving towards selective load control. Under this arrangement, lower electricity prices would be given to electric vehicle users whose battery chargers could be briefly interrupted (by remote control) at occasional times of excessive total demand for electricity.

Until utilities offer these innovative rates, however, users of electric vehicles are likely to begin recharging immediately at the end of each day's driving. This would be the most convenient method and--under most existing rates--no more expensive. But it would add to existing peak loads, straining available and planned generating facilities. It would also require more petroleum than recharging late at night, when more coal-fired electric generating capability would otherwise be available to generate recharge power.

In recent years, electric utilities have avoided use of petroleum-fired generating plants and installed new generating facilities using other sources of energy. In 1979, this resulted in the use of petroleum for only about 15 percent of all generation in the US. In many areas of the country, utilities use little or no petroleum and so could accommodate electric vehicle recharging without any substantial additional use of petroleum. Elsewhere, however, where utilities have a mix of facilities and fuels available, it is petroleum-fired plants which are idled as demand drops each night; and it is these plants which would have to be restarted to recharge electric vehicles overnight. Overall, some 30 percent of recharge energy would come from petroleum if electric vehicles were distributed uniformly in the United States in 1980. By 2000, this figure will fall to little more than 10 percent, owing to the greater reliance planned on non-petroleum energy sources.

Though much of the electricity supply infrastructure needed for electric vehicles is already in place, some vehicles are not readily accessable to recharging outlets. Although the data are poor, it appears that roughly 25 percent of cars and light trucks in the US are parked on the street overnight, rather than in a garage or carport where electric outlets are either already available or could be installed (for roughly $100-300). Only about half of all US cars and light trucks in personal use are at single family housing units with off-street parking, where electricity is most readily available. Adding electric outlets in parking garages and parking lots may cost $400-500 per parking space, a significant expense (though much less than the differential between the prices of electric and conventional vehicles). An alternative to home recharges would be service stations offering quick recharges or battery swaps, but this would be a much more expensive way to deliver electricity to vehicles.

The materials supply industry is also a vital component of the infrastructure required to support electric and hybrid vehicles. In addition to the materials required in conventional cars, electric vehicles will demand large quantities of new materials for batteries. Expanding extraction and refining capabilities to support production of several million electric vehicles annually in the 1990s appears feasible. Much higher levels of production, however, could bring problems. In this context, world resources of some battery materials appear no more abundant than world resources of petroleum. Mass production of nickel-iron and nickel-zinc batteries, for example, could lead to substantial increases in imports of nickel and cobalt. Formation of international cartels to control supplies and prices is a possibility. Other types of batteries, however, rely on materials which are abundantly available in the United States (lead, zinc, chlorine, lithium, sulfur). Moreover, once an inventory of batteries is established, effective recycling of battery materials should drastically reduce needs for additional new materials from either imports or domestic production.

The motor vehicle industry could produce, sell, and service electric and hybrid vehicles without drastic changes in its structure. The major change required would be a shift of activity and employment from service stations to battery manufacturing and sales. Though service has often been a problem for the electric vehicles produced recently in very small quantity by small businesses, it appears the major auto makers have the organizations, procedures, and expertise to achieve reliable designs, effective training of mechanics, and adequate provision of spare parts for electric and hybrid vehicles.

The market penetration of electric and hybrid vehicles is uncertain, raising significant risks for both government and industry development programs. Existing projections of the number of electric and hybrid vehicles in the US fleet by the year 2000 range from about one percent all the way up to about 10 percent. At the low end of this range, mass production of electric and hybrid vehicles may not be profitable or economically viable.

Market penetration depend strongly on many uncertain factors:

- Future battery technology, and particularly the operating life and consequent depreciation costs.
- The performance, fuel economy, and reliability of future competing conventional cars, which are likely to improve continually.
- The availability of liquid fuels for motor vehicles, in cluding gasoline from domestic or imported petroleum, gasoline made from shale oil or coal, methanol, and liquified petroleum gases (LPG).
- The cost of liquid fuels relative to the cost of living and the cost of recharge electricity.

All these factors have important effects on the relative benefit to the motorist of electric and hybrid vehicles which are wholly or partially independent of liquid fuels, but considerably more expensive to buy than comparable conventional vehicles.

For electric (but not hybrid) vehicles, marketability also depends strongly on the value consumers attach to range between refueling or recharging, a subject about which little is known. On the one hand, travel surveys show that on a typical day, 95 percent of all motorists drive less than 100 miles, and 95 percent of secondary drivers (drivers traveling least at multi-driver households) travel less than 50 miles. On the other hand, consumer surveys show motorists attach large dollar values to long range and quick refueling capability. (From one survey, it appears urban motorists would pay over $4,000 extra to increase driving range from 50 to 200 miles.)

Generally, operators of commercial vehicle fleets also indicate demanding range requirements as well. In a few commercial applications, however, range and speed requirements are low and driving conditions (frequent stops and starts with long periods of idling) adversely affect the life and fuel consumption of conventional vehicles. In these applications, such as mail delivery, utility meter reading, and servicing of urban coin telephones, electric vehicles promise to be competitive in the near future. Only a few percent of all commercial fleet vehicles, however, are in such service.

The principal benefits and costs of large-scale use of electric vehicles are illustrated by the following:

- Energy. Nationwide electrification of 20 percent of annual car and light truck travel in 2010 would reduce automotive petroleum use by around 18 percent. If electric vehicles were introduced only in regions where utilities would use little or no petroleum for generating recharge electricity, up to 70 percent of annual travel could be electrified with almost no use of petroleum.

- Environment. Electrification eliminates exhaust emissions from vehicles but would increase sulfur oxide emissions from fossil-fueled power plants. On balance there would appear to be an improvement in air quality, but it is small. Stringent controls are being applied to pollutant emissions both from motor vehicles and electric utilities. Thus pollutant emissions from other sources will largely mask changes due to vehicular electrification. Because electric propulsion is extremely quiet, it would reduce traffic noise; but again, reductions would be small because of the dominant roles played by large trucks and tire noise. Tire noise, of course, will be the same for both electric and conventional vehicles.

- Economy. Use of electric and hybrid vehicles would increase motorists' cost of travel, at least until gasoline becomes much more expensive or very advanced batteries are developed. Changes elsewhere in the economy would be relatively small. The motor vehicle industry accounts for less than 4 percent of US employment, and many jobs within it (production of vehicle bodies, running gear, and tires; vehicle distribution and sales; parts supply) would be little changed by electrification. Year-to-year changes required for 20 percent electrification of US light vehicle travel by 2000 or 2010 would be very small.

- Resources. Known resources of most battery materials would be adequate for electrifying 20 percent of US car and light truck travel; but problems would arise for many battery types if there were to be worldwide vehicular electrification on a large scale. Increased demand due to electrification would increase prices particularly for lithium, cobalt, and nickel. Generalized data suggests that increasing prices would lead to increased exploration, improved methods of extraction, and thus expanded reserves and resources; but this is at best speculative.

- Transportation. Electric vehicles could provide substantial mobility in the absence of petroleum, with potentially low maintenance, high reliability, and a smooth, quiet ride. Today's levels of mobility, however, would be impaired by the range limitation of electric vehicles, and high acceleration capability would be unavailable or uneconomic. Hybrids could provide unimpaired mobility and, with higher use of petroleum, unimpaired acceleration capability as well.

The uncertainties in these projections of benefits and costs primarily arise in the uncertain market penetration of electric and hybrid vehicles (discussed above) and in the future growth and utilitization of the electric and utility industry. Growth rates of electricity demand are uncertain and may change; if they increase, utilities may have less capacity available for recharging electric cars. Patterns of demand may also change; the same time-of-day pricing which encourages the desirable late-night recharging of electric vehicles might smooth out daily fluctuations in other demands. Then little capacity would ordinarily be idle late at night and thus available for electric vehicle recharging.

2 INTRODUCTION

This report presents a comprehensive review of the future of electric and hybrid vehicles through the year 2010 in the United States. It discusses the technology, performance, and limitations of probable future electric and hybrid vehicles; the infrastructure necessary to produce and support them; marketability; and finally, effects on the nation if used in large numbers.

The report begins with a discussion of the technology of electric vehicles, and what it may offer in the future. Storage batteries are addressed first because they have always been the principal obstacle to practical electric vehicles. Then electric drive trains and their integration into vehicle design are described. Next, the tradeoff between range and cost is projected. (Electric vehicles may offer competitive cost or long driving range, but probably not both at once.) Finally, the performance and cost of representative future electric vehicles are projected. These are used subsequently in the report as the basis for considering marketability and the impacts of large-scale use.

The technology of hybrid vehicles is discussed after that of electric vehicles because hybrids are an extension of electric vehicle technology which will probably reach the marketplace only after the appearance of electric vehicles, and only if satisfactory storage batteries and electric drive trains have been developed. The hybrid vehicle designs described here are basically electric vehicles to which an internal-combustion engine has been added. The engine supplements the energy and power available from the electric drive, giving either unlimited cruising range or both the range and the high acceleration performance of conventional cars. The performance and costs of representative future hybrid vehicles are projected and compared with those of future electric vehicles. Because range-extension hybrids could electrify light vehicle travel in the US to about the same extent as pure electric vehicles, most of the impacts of hybrid vehicle use on a large scale are similar to those of pure electric vehicles.

After reviewing the potential of electric and hybrid vehicle technology, the report turns to consideration of the infrastructure required to support electrified travel. The principal elements of the infrastructure are the electric power system, which must recharge batteries; the materials industry, which must supply large quantities of materials used in batteries; and the automotive industry, which must both produce and maintain electric vehicles. The discussion begins with electric utilities, an industry larger in the United States than the motor vehicle manufacturing industry, without which electric cars would not be feasible. Materials supply is discussed next. It is, after all, a shortage of petroleum resources and supplies that motivates consideration of electric vehicles, and resources of battery materials are not necessarily more abundant or more assuredly available from foreign suppliers.

Marketability of electric and hybrid vehicles is next reviewed. The discussion begins with existing patterns of vehicle use, since it is often argued--correctly--that future electric vehicles will have adequate range and speed for most urban travel. Market penetration estimates, however, show clearly that this is not enough to ensure large sales of electric and hybrid vehicles, since buyers are concerned about initial costs as well as limited range and lengthy recharge times. The discussion of marketability points out the critical role of the cost and availability of liquid fuels for heat engine vehicles, and the possible effect of incentives for electric and hybrid vehicles which may be provided by governmental action.

This report concludes with a review of the benefits and costs, monetary and non-monetary, which might accrue if electric and hybrid vehicles were to be widely used in the United States. It begins with energy, since that is the principal problem motivating consideration of electric vehicles. It considers both the petroleum requirements of electric utilities to generate power for recharging electric vehicles and the petroleum savings if conventional vehicles were to be replaced with electric and hybrid vehicles. It next turns to the environment, specifically air pollution and traffic noise. Though electric vehicles emit no air pollutants directly, the power plants which recharge them will run overtime to do so. The effects on the economy of manufacturing and supporting electric vehicles are briefly reviewed, as are resultant demands for battery materials, limitations of US materials resources, and potential dependence on foreign suppliers. The effects of limited-range vehicles on mobility and travel in the US are noted. Finally, the major uncertainties in projecting benefits and costs of electrification are reviewed. The uncertainties arise at every step, in the projection of technological capability and costs, infrastructure, and marketability, as well as in the final accounting of national benefits and costs.

The material presented here is drawn from existing studies. No new analyses were undertaken. Instead, this report offers a comprehensive review for a nontechnical audience. Each chapter begins with an introduction and summary which provides historical background and explains key issues before presenting projections for the future. Graphs and tables are presented only as supplements to material presented in the text, and mathematical models are avoided.

3 ELECTRIC VEHICLE SYSTEMS

3.1 INTRODUCTION AND SUMMARY

An electric vehicle is propelled by an electric motor drawing power from an electric storage battery. The motor and battery take the place of the engine and fuel tank of a conventional car. The battery is rechargeable: when it runs down, after perhaps 50 to 100 miles of driving, it may be recharged by a battery charger connected to a standard electrical outlet. Recharging typically requires 4 to 12 hours.

The technology to build electric vehicles has been available for almost a century. Eighty years ago, in the early days of the automobile, electric vehicles were as numerous in the United States as gasoline and steam-powered vehicles. By the 1920's, however, electric vehicles had almost vanished from the vehicle marketplace, primarily because of limited range and higher cost than competing gasoline-powered vehicles.

Though the limited range and lengthy recharge of the electric vehicles are important drawbacks, they are offset by a major advantage: independence of the gasoline pump. Today, intense interest in electric vehicles has been reawakened by the increasing price and uncertain availability of petroleum fuel for conventional vehicles. Furthermore, programs of battery R&D initiated in response to the petroleum problem offer prospects of more competitive electric vehicles, with much longer ranges and lower costs than previously possible.

Improved batteries are plainly the key to more capable and economical electric vehicles. Throughout the history of electric highway vehicles, storage batteries have been heavy, expensive, short-lived, and limited in capability. The lead-acid storage batteries used in the typical electric car of the 1970's may be accurately likened to a gasoline tank weighing a thousand pounds, costing over $1,000, requiring replacement every 10,000 miles, and carrying only two gallons of fuel. This sort of fuel storage would add some 50 percent to the empty weight of a subcompact car, increase its operating costs by adding battery depreciation of perhaps ten cents per mile, and limit its range to around 40 miles of urban driving.

Battery R&D during the late 1970's has already increased energy storage of the lead-acid battery by over 20 percent and nearly doubled its useful life. For the future, even larger improvements seem likely, though projections are uncertain and it is impossible to predict confidently which of several competing battery types will prove best. Longer useful life is ordinarily the major problem; it is relatively easy to build batteries with increased energy storage if long life is not required.

Batteries under development for the near-term--that is, batteries which may be ready for mass production during the 1980's--include improved versions of the familiar lead-acid battery and the less-common nickel-iron battery, plus two batteries which have never before been used in commercial electric vehicles, nickel-zinc and zinc-chlorine. Depending on which of these developments is successful, energy storage per pound may be 35-100 percent greater than that of the best lead-acid batteries of 1980, and improvements in operating life may be even greater.

More advanced batteries may also be successfully developed, probably in time for mass production during the 1990's, though this is even less certain. Again, there are a number of competing systems. The best of them might provide up to 4 times the energy storage per pound of the best 1980 batteries, or last the entire life of the vehicle they power.

The 100-mile electric car, a goal stated by both DOE and GM, will become a practical possibility during the 1980's if any of the near-term battery developments are successful. The weight and cost of the car, however, will remain high. Depending on battery type, curb weight of a four-passenger 100-mile subcompact might range from 3000 to 4000 lbs, or 50 to 100 percent above that of a comparable conventional subcompact car. Projected sticker prices (in 1980 dollars) range from $8000 to $8500, or 60-75 percent above the projected price of a comparable conventional subcompact.

Life-cycle costs projected for near-term electric cars are much closer to the life-cycle cost of the comparable conventional car, but still above it. Including depreciation, maintenance and repairs, insurance, parking, electricity, and financing, life-cycle costs projected for four-passenger electric cars range from 22.0 to 26.6 cents per mile in 1980 dollars. The life-cycle cost projected for the comparable conventional car is 21.4 cents per mile. The projected electric cars benefit from longer useful life, from low costs per mile for electricity, and from relatively low maintenance and repair costs. Resultant savings are outweighed, however, by battery depreciation costs plus extra depreciation and financing costs due to the higher initial cost of the electric vehicles.

If cars with more advanced batteries become available in the 1990's, they may be substantially lighter and less expensive than the near-term cars, though still heavier and more expensive to buy than a comparable conventional car. Life-cycle costs, however, could be less than those of the conventional subcompact, even if gasoline prices are no higher than in 1980.

After battery performance, life, and cost, the biggest uncertainties in these projections are the future prices of gasoline and electricity. If electricity prices remain constant, real increases in the price of gasoline from 10 to over 100 percent, depending on the battery type, would be required to make the conventional car as expensive as the near-term electric cars.

Maximum range in actual use is also uncertain. The hundred-mile figure projected here is a nominal figure for stop-start urban driving. Depending on driving speed, battery age, frequency of stops, grades, headwinds, and use of air conditioning, actual maximum range could be more or less than the nominal by a factor of two.

The 1980 state of the art in electric car technology is best exemplified by the Electric Test Vehicle (ETV-1) built for DOE by General Electric and Chrysler. This car is shown in Fig. 3.1. It is an attractive four-passenger subcompact with sufficient speed for freeway use and a useful urban driving range which may be about 60 miles. (Testing is presently incomplete; two preliminary trials showed urban ranges of 50 and 74 miles.) The initial price of the ETV-1 in full-scale mass production is estimated by GE and Chrysler at $8500 (in 1980 dollars), 63 percent above the $5200 price of a comparable 1980 Chrysler subcompact with an internal combustion engine (ICE).

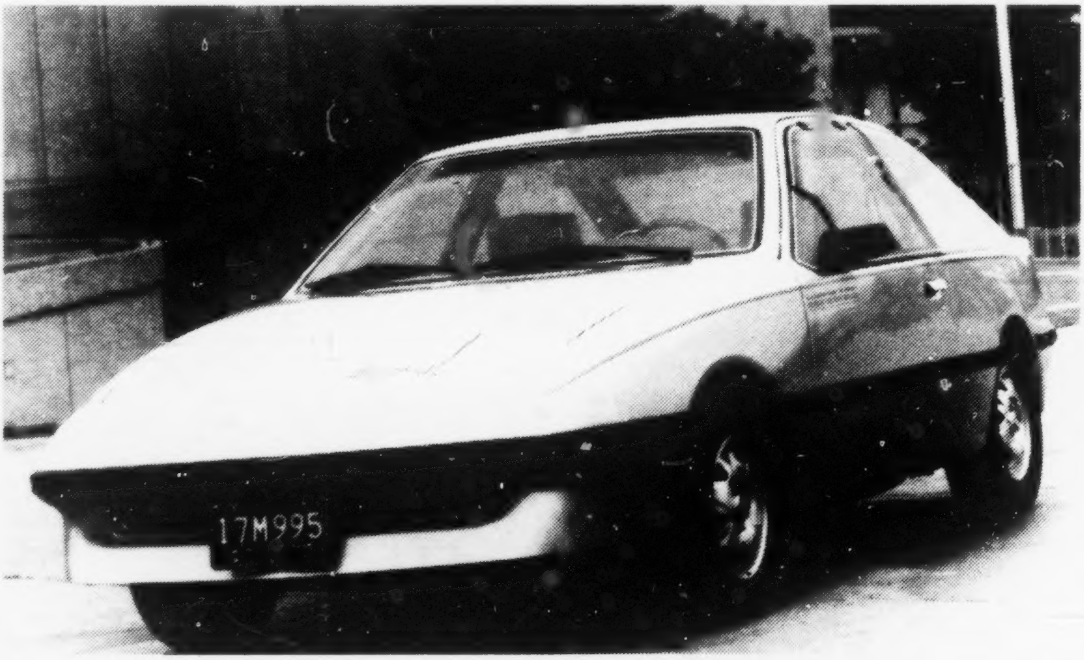

Figure 3.1 The GE/Chrysler Electric Car ETV-1

The near-term electric cars projected here might be generally similar in appearance and capability to the ETV-1. Like the ETV-1, they would carry four passengers at speeds adequate for freeway use. Their improved batteries, however, would give them much more range at little or no extra cost. Furthermore, their acceleration capability would be about 30 percent higher. On level ground they could accelerate from 0 to 40 mph in 10 seconds: this is comparable to the capability of many diesel automobiles, and considerably better than the ETV-1 capability for accelerating from 0 to 40 mph in 14 seconds.

The remainder of this chapter details projections of the performance and cost of future electric vehicles. It begins with batteries because they are the crucial problem for electric vehicles. Next, it describes electric drive technology: motors, controllers, and other components. It then devotes three sections to complete electric vehicles: design objectives and requirements, the major tradeoffs between performance and cost, and the characteristics of electric vehicles chosen to be representative of future possibilities.

3.2 BATTERIES

Background

The limited capability, high cost, and short life of the storage battery have long been the principal obstacles to electric vehicles competitive with conventional vehicles. In the early 1900's, when motor vehicles were in their infancy and there were as many electric as gasoline vehicles in use, contemporary authorities praised the cleanliness, safety, ease of operation, and reliability of electric propulsion, but bemoaned the immense weight and limited capability of the storage batteries.[1] In explaining the demise of the electric vehicle, historians note in addition the rapid deterioration of storage batteries with use, the high overall costs of operating the electric vehicle, and the relatively slow technological progress in storage batteries relative to that in internal-combustion engines.[2] Even today, golf car batteries are still made in the same general configuration as that of the early 1900's by a procedure patented in 1881.

Most electric vehicles built in the 1970's are powered by lead-acid batteries designed for golf cars. These batteries physically resemble the starting-lighting ignition batteries used in conventional automobiles, but are somewhat larger, and are designed for repeated deep discharges. Four-passenger electric cars have typically required 1000-1200 pounds of golf-car batteries costing $1000-1200 to achieve perhaps 40 miles of urban driving between recharges. Since the batteries could be recharged only about 250 times, replacement was required after each 10,000 miles of driving. Thus battery depreciation alone has amounted to around ten cents per mile.

The basic cell of the lead-acid battery (and most other batteries) consists of two dissimilar materials immersed in a liquid electrolyte.

During discharge, an electrochemical reaction takes place between these materials which causes an electric current to flow through an external circuit, connected between them, such as an electric motor. As the original materials in the cell are consumed in the reaction, chemical energy is transformed into electrical energy. During recharge, the electric current through the cell is reversed by electric energy from an external source. This reverses the chemical reaction within the cell, re-forming the original chemical compounds and thus storing electrical energy in chemical form.

Recharging does not return the cell exactly to its original condition. With repeated cycles of charge and discharge, fully-charged cells depart further and further from their original state. This limits the useful life of the cell: eventually, the quantity of energy stored and the maximum power output (the rate at which energy can be released) will fall below acceptable levels, or the cumulative movement of material within the cell may develop internal short circuits.

A battery is an assemblage of interconnected cells. The standard golf-car battery comprises three cells. Electric vehicle batteries ordinarily require 48 to 72 cells. For convenience in handling and economy of manufacture, the 3-cell golf car battery rather than the single cell has usually served as the basic module from which complete vehicular batteries are assembled. By proper interconnection, the completed battery may operate at an output voltage as high as the sum of all its cell voltages, as low as the voltage of a single cell, or at various intermediate levels. For electric vehicles, all cells are usually connected in series to give battery voltages in the range of 72-144 volts.

It should be noted that many batteries are not designed for recharging. Such batteries, called primary batteries, are widely used in flashlights, transistor radios, and other devices where battery life and cost are acceptable without recharging. Batteries not designed for recharge can be light, cheap, and powerful; but replacement costs would generally be intolerable if primary batteries were used for vehicular propulsion.

In conventional batteries, all the active materials remain in the basic cell during the complete cycle of charge and discharge. In one promising new development, however, one of the active materials is stored separately and is moved to and from the cell by mechanical pumps (the zinc-chlorine system under development by Gulf and Western Industries). The system is electrically recharged, however, without physical introduction of new active material from external sources. This is a critical distinction because it determines whether the electric utility system, or some other system, would be required to deliver energy to automotive propulsion batteries.

In this report, only electrically rechargeable batteries are considered. Thus the aluminum-air battery being investigated by

Lawrence Livermore Laboratories is omitted. It would be recharged by replacement of its aluminum plates, with periodic removal of the electrolyte containing spent aluminum. A major new chemical reprocessing industry and refueling infrastructure would be required to recycle the spent aluminum into new aluminum plates. Similarly, fuel cells are also omitted. In a fuel cell, active material such as hydrogen and oxygen are combined to release electric energy. These fuels are stored outside of the cell, however, and are not regenerated by forcing electricity in the reverse direction through the cell. Again, a new chemical industry and refueling infrastructure would be required to refuel electric vehicles using fuel cells.

To recharge the storage batteries considered in this report, electric energy from an ordinary electrical outlet is passed through a battery charger into the battery. The battery charger converts ordinary alternating currents to the direct currents required by the batteries. It provides the direct current at a voltage appropriate to the state of battery charge and to the rate of recharge desired.

The useful life of a battery, the number of times it can be fully charged and discharged, depends strongly on how it is recharged. If the battery is deeply discharged, much of its charge can be restored without harmful effects quite rapidly--50 to 75 percent in the first hour, if sufficient electricity is available and a high-power charger is available to supply it to the battery. Completing the charge, however, must generally be done slowly. For lead-acid batteries, at least 4 or 5 hours is required to reach full charge even after a shallow discharge. To avoid the expense of very high-capacity electric outlets and high-power chargers, it is customary to install equipment which requires all night (8 hours or more) to recharge a deeply discharged battery.

Measures of Performance and Cost

For evaluating the performance and cost of batteries for vehicular propulsion, 5 measures are in common use.

- Specific energy is the electrical energy in watt-hours which can be delivered by each pound or kilogram of battery. Because specific energy depends on discharge rate, it is customary to measure specific energy during a three-hour discharge, which is roughly the time required for full discharge in continuous driving of a passenger vehicle. High specific energy is vital for vehicle batteries because it determines vehicle range. If specific energy is increased, the range of the vehicle using the battery will be increased a little more than proportionately.

- Specific power is the maximum power in watts which can be delivered by each pound or kilogram of battery. Since the capability of a battery diminishes rapidly as it approaches the fully discharged condition, it is necessary to state carefully the conditions under which specific power is measured. It is customary to measure specific power when the battery is half discharged, and to make the measurement on a conservative basis which indicates about 10 percent less than the maximum which could actually then be obtained. Specific power is important because it determines the maximum electrical power available in a vehicle for acceleration or climbing hills.

- The life of a battery is ordinarily stated in terms of the number of deep discharge and subsequent recharge cycles the battery can withstand. Life is tested by repeated cycles of discharge and charge which each withdraw 80 percent of rated battery capacity. Rated capacity is the maximum energy which a new battery can supply in a three-hour discharge. Battery life is considered ended when the battery is no longer capable of delivering 80 percent of its rating during discharge. Cycle life depends on many factors, such as battery temperature and the manner of charging and discharging; and it slowly diminishes with the passage of time even in the absence of use. Relatively little is known about the life of batteries which are subjected to shallow rather than deep discharges, or discharges of varying depth. For lack of better information, it is customary to assume that the total energy deliverable by a battery during its life is unaffected by the depth of discharge. For vehicles, this means that the total mileage which can be driven on a set of batteries is independent of the distance driven each day. Battery life is critical for vehicular applications because it determines the frequency of battery replacement and thus affects total battery costs during the life of the vehicle.

- Energy efficiency is the electrical energy delivered by a battery expressed as a percentage of the electrical energy required for recharge. It is important because it determines the amount of propulsion energy the battery can deliver from a unit of recharge energy. Some batteries require electric energy from external sources for heating or refrigeration. It is customary to include this energy with energy for recharging in estimating efficiency because it affects total electricity requirements in the same way as other losses within the battery.

- Specific cost is the cost of each kilowatt-hour of battery capacity. It is important because it determines the initial and replacement cost of a battery of a given storage capacity. Like all other costs in this report, battery costs are measured in mid-1980 dollars and are based on mature mass production and high-volume retailing.

To compare possible future batteries and to compute their implications for electric vehicles (vehicle driving range, energy use, and cost), it is necessary next to project specific values of these five battery measures for a representative set of future batteries.

Projections of Performance and Cost

The following projections are based on published reports which are generally the product of the DOE battery R&D program.[3] There also exist substantial independent programs of battery development, such as the GM work in lead-acid, nickel-zinc, and high-temperature lithium batteries. Published results are insufficient, however, for use of industry-supported research here.

Batteries under development by the Department of Energy are divided into two groups: "near-term" and "advanced." Near-term batteries are those considered most likely to become available for use in demonstration electric vehicles before 1985. Advanced batteries offer higher performance potential but successful development is far less certain and development schedules are speculative. It appears quite likely that at least one of the near-term batteries will be successfully mass-produced for vehicular propulsion by 1990. It is too early, however, to determine which of the batteries will succeed, so all four near-term batteries are included in the projections presented here. Advanced battery developments are far less predictable, but there is a reasonable possibility that some kind of advanced battery will follow the near-term batteries into mass production before the year 2000. To illustrate this possibility, projections are presented for batteries representative of low and high levels of advanced battery performance. The four types of near-term batteries are lead-acid, nickel-iron, nickel-zinc, and zinc-chlorine. An improved zinc-chlorine system and a high-temperature lithium-metal sulfide system were taken as representative of the lowest and highest levels of performance to be expected from advanced batteries.

Specific energies projected here for the near-term batteries are 1.6 to 2.5 times larger than those of premium golf-car batteries of the 1970's. Specific energies projected for the advanced batteries are 3 and 5 times those of premium golf-car batteries. Because electric car ranges are roughly proportional to specific energy, these increases imply dramatic improvements are coming in useful range.

Major improvements in life are also expected. For the near-term batteries, cycle lives are projected to be 1.6 to 6 times longer than those of premium golf-car batteries. For the advanced batteries, projected cycle lives are 4 to 6 times longer. With these life increases, batteries might be replaced only once or twice during the life of the vehicle they power. In some cases, they might last the entire life of the vehicle. Even though the specific costs of the projected batteries equal or exceed those of golf-car batteries, the long lives projected would drastically reduce expenditures necessary for replacement batteries, and total battery cost over the life of the vehicle.

Table 3.1 summarizes the ranges of performance and cost projected for near-term and advanced batteries. It includes corresponding data for premium golf-car batteries commonly used in electric vehicles during the 1970's. It also includes data for a battery representing 1980 capability. This battery, the Globe-Union EV2-13, was developed for the DOE Electric Test Vehicle ETV-1.[4] It embodies substantial advances over the golf-car batteries of the seventies; commercial production is expected during 1981.

Tables 3.2 and 3.3 provide more detail to support Table 3.1. In Table 3.2, individual projections are advanced for the four near-term batteries. These projections are based on the development goals adopted by DOE, but include downward adjustments in specific energy and life reflecting two considerations: progress for some of the near-term batteries, notably lead-acid and zinc-chlorine, seems to be more rapid than for the others; and development goals have been set higher than probable achievements in order to pose a significant technical challenge and elicit the best possible results. In Table 3.3, the maximum performance now contemplated for advanced batteries is illustrated by a lithium-metal sulfide system. A reasonable minimum level of performance for advanced batteries is illustrated by an improved zinc-chlorine system. In general, performance goals adopted by DOE for advanced batteries, including sodium-sulfur, metal-air, and other systems in addition to lithium-metal sulfide, lie between these examples in Table 3.3. The long lives and low costs in the table are both optimistic and speculative.

The lead-acid battery projected in Table 3.2 is based on vast experience: lead-acid batteries today provide starting, lighting, and ignition for hundreds of millions of passenger cars and tens of millions of motor trucks; and they provide motive power for tens of thousands of forklift trucks. The battery sought for on-road electric vehicles would bring together the high energy, high power, and low cost of the starting-lighting-ignition battery with the extremely long service life (1500-2000 deep discharges) achieved in motive power batteries for industrial lift trucks. The construction of a battery representing the state of the art in 1980 is illustrated in Fig. 3.2, which shows the battery that was especially developed for the ETV-1 car built by GE and Chrysler.[4] Like most other lead-acid batteries used in electric vehicles, this battery has three cells and weighs about 60 pounds. Each cell includes a set of positive and negative electrodes--in this case lead grids supporting the active materials, spongy lead and lead dioxide. The plates are immersed in a dilute solution of sulfuric acid, the electrolyte for the electrochemical reaction in which lead sulfate is formed as electric energy is delivered to an external circuit. Sixteen to twenty such batteries are usually required in a four-passenger electric car. They are typically placed on a supporting tray, connected in series, and loaded into the vehicle they are to propel from underneath. In the 1970's, it was necessary every few weeks to remove the cap for each of the 60 cells in a vehicle battery pack, add distilled

TABLE 3.1

PROJECTED IMPROVEMENTS IN PROPULSION BATTERIES

Battery Type	Availability (in quantity)	Specific Energy,[1] Wh/lb (Wh/kg)	Specific Power,[2] W/lb (W/kg)	Life, Deep Discharge Cycles[3]	Specific Cost,[4] 1980 dollars/kWh
Golf-Car	1970-1980	14 (30)	32 (70)	250	55
EV2-13[5]	--	17	51 (112)	500	--
Near-Term	By 1990	23-34 (50-75)	50-54 (110-120)	400-1500	55-90
Advanced	By 2000	45-68 (100-150)	68-136 (150-300)	1000-2000	60

Source: Tables 3.2, 3.3, Ref. 3.

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[1] For discharge at the three-hour rate, in Watt-hours per pound (or kilograms)

[2] For 20 seconds at 50 percent state of charge, in Watts per pound (or kilogram)

[3] For 80 percent depth of discharge during each cycle.

[4] Retail price (including markup of 30 percent added to the large-quantity factory price) for batteries in the 30-kWh class, in 1980 dollars, given mass production.

[5] This is the improved battery developed for the DOE Electric Test Vehicle ETV-1. It has not been put into production.

TABLE 3.2

ASSUMED PERFORMANCE AND COST FOR NEAR-TERM PROPULSION BATTERIES

(TO BE MASS-PRODUCED BY 1990)

Battery	Specific Energy,[1]		Specific Power,[2]		Life, Deep-Discharge Cycles[3]	Energy Efficiency percent[4]	Specific Cost, $/kWh[5]
	Wh/lb	Wh/kg	W/lb	W/kg			
Lead-Acid	23	50	54	120	800	80	55
Nickel-Iron	27	60	54	120	600	65	90
Nickel-Zinc	32	70	68	150	400	75	90
Zinc-Chlorine	34	75	50	110	1500	55[6]	90

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[1] For discharge at the three-hour rate, in Watt-hours per pound (or kilogram)

[2] For 20 sec at 50 percent state of charge, in Watts per pound (or kilogram)

[3] For 80 percent depth of discharge.

[4] Electric energy output relative to energy input.

[5] Retail price (including markup of 30 percent added to the large-quantity factory price) for batteries in the 30 kWh size class, in 1980 dollars.

[6] Includes charger.

TABLE 3.3

ASSUMED PERFORMANCE AND COST FOR ADVANCED PROPULSION BATTERIES

(TO BE MASS-PRODUCED BY 2000)

Battery	Specific Energy,[1]		Specific Power,[2]		Life, Deep-Discharge Cycles[3]	Energy Efficiency, percent[4]	Specific Cost, $/kWh[5]
	Wh/lb	Wh/kg	W/lb	W/kg			
Zinc-Chlorine	45	100	68	150	2000	60[6]	60
Lithium-Metal Sulfide	68	150	136	300	1000	70	60

---

[1] For discharge at the three-hour rate, in Watt-hours per pound (or kilogram)

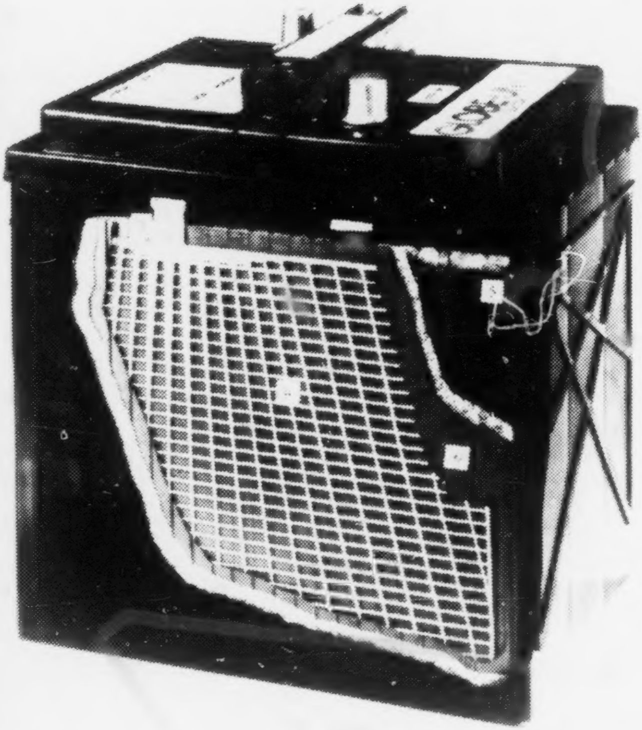
[2] For 20 sec at 50 percent state of charge, in Watts per pound (or kilogram)

[3] For 80 percent depth of discharge.

[4] Electric energy output relative to energy input.

[5] Retail price (including markup of 30 percent added to the large-quantity factory price) for batteries in the 30-50 kWh size class, in 1980 dollars.

[6] Includes charger.



GLOBE-UNION INC.

EV2-13 LEAD-ACID
ELECTRIC VEHICLE BATTERY

- 6 Volt
- 27.2 kg (60 lb)
- Unconventional, Computer-Designed Cell Geometry
- Left-Hand and Right-Hand Models

KEY

1. Thin, Lightweight, Durable Polypropylene Container and Cover Thermally Welded for a Leak-Free Assembly
2. Single-Point Watering System with Safety Venting
3. Low-Resistance, Through-the-Partition Intercell Welds
4. High-Efficiency, Computer Designed Radial Grids
5. Optimized Active Materials
6. Submicro Polyethylene Envelope Separators with Glass Mat

Figure 3.2 Current Globe-Union Lead-Acid Electric Vehicle Battery

water as necessary to each cell, replace the caps, and clean off the accumulation of acid moisture and dirt which appeared on the battery surface. Future batteries, however, will have single-point watering and venting systems which will greatly reduce the labor of maintenance. The interim state-of-the-art batteries developed for and now being tested by DOE already have such a system, and in addition appear to be close to all the projections of Table 3.2 for lead-acid batteries excepting specific energy, where they offer about 20 percent less.[5] Further development toward the DOE advanced lead-acid battery goal (27 watt-hours per pound) should bring the energy level up at least to the figure of Table 3.2 (23 watt-hours per pound) during the 1980's.

The nickel-iron battery was invented by Thomas Edison at the turn of the century. Though it failed to achieve his express intention--making electric vehicles superior to gasoline vehicles--it has found continued use in railway carriages, mine locomotives, and other applications requiring a rugged, durable, long-life battery. The development problem for on-road vehicular applications is to increase power and energy density and to lower costs, without undue sacrifice of life. The nickel-iron and nickel-zinc batteries of Table 3.2 are generally similar in arrangement to the lead-acid battery. Both the nickel-iron and nickel-zinc batteries employ multi-plate cells with an aqueous electrolyte at room temperature--though in this case the electrolyte is alkaline rather than acid (a solution of potassium hydroxide). Both batteries employ nickel positive electrodes, but the nickel-zinc battery substitutes zinc for iron negative electrodes to achieve higher energy and power output per pound of battery. A practical nickel-zinc battery has long eluded developers primarily because of problems inherent in this substitution. On repeated cycles of charge and discharge, zinc electrodes tend to change shape, lose capacity, and grow needle-like dendrites which penetrate the separators between adjacent positive and negative plates, thus short-circuiting cells.

The zinc-chlorine battery of Table 3.2 differs substantially in construction from the other near-term batteries. One of its active materials, chlorine, is stored separately from the electrode stack, and must be conveyed to and from the stack by a system of pumps and plumbing through which the electrolyte, an aqueous solution of zinc chloride containing gaseous chlorine, is circulated. The chlorine is stored as a solid, chlorine hydrate, which forms when water containing chlorine is chilled below 50 degrees. To accomplish this, the battery charger includes a refrigerator to chill a working fluid. During charging, the chilled working fluid is pumped through a heat exchanger within the battery, where it absorbs heat from the electrolyte. The electrodes in the cells of this battery are based on graphite structures which offer very long life. During charging, zinc is plated onto the negative electrodes while chlorine is evolved at the positive electrodes. The chlorine is carried out of the cell stack by the circulating electrolyte through the heat exchanger where chlorine hydrate is formed. During discharge, the process is reversed. Because the battery may be fully discharged without harm, all the zinc may thus be periodically removed from the graphite substrates. In this way, the usual problems of zinc electrodes, cumulative shape change and dendrite buildup during cycling, may be eliminated. It appears that the pumps and plumbing, rather than the electrodes, may ultimately limit the life of the battery. It seems possible, and even likely, that sufficient life can be achieved so that the battery may be sealed in a container with terminals for input and output of electricity, and operated without servicing for the entire life of the vehicle.

The zinc-chlorine system is relatively new and may be developed well beyond the levels of performance projected in Table 3.2. Accordingly, an advanced zinc-chlorine system is projected in Table 3.3, where it is representative of the minimum performance which advanced battery developments, if successful, may bring in the 1990s.[6]

The lithium-metal sulfide system in Table 3.3 is an example of the highest performance which advanced battery systems may bring. Its characteristics are drawn from the most optimistic long-term development goals which have been published in recent years. The cells of this battery utilize lithium-aluminum negative plates and iron sulfide positive plates immersed in a molten salt electrolyte. The battery must be maintained at approximately 700° F, which means that a housing with exceptionally effective insulation is required. It is highly desirable that heat loss through the housing be low so that additional heat beyond that evolved in the cells during ordinary use will be unnecessary. If supplementary heating is necessary, it will be supplied by the battery charger, decreasing effective battery efficiency. In addition to superb insulation, the housing must also ensure safe containment of battery materials, even in crashes. The assumed specific energy in Table 3.3 includes a weight allowance for housing, which may amount to 20 or 25 percent of total cell weight.[7] The high energy of the battery is due to the high chemical activity of lithium and sulfur. The principal difficulties in battery development are also due to this high activity, which presents serious problems of corrosion and containment, especially at the elevated temperature of operation. Extraordinary materials are needed to contain the molten electrolyte, to separate and space the plates within each cell, to collect and conduct electric currents within each cell, and to insulate the conductors where they pass through the cell container. These materials must nonetheless be inexpensive to purchase and fabricate.

In general, achieving a long operating life appears to be the major problem in battery development. There is little theory to guide improvements intended to combat the gradual changes and degradation associated with charge-discharge cycling. Experimental approaches are difficult and very time-consuming, since it may take years of testing to determine the effect on battery life of a given design change. Though increases in energy density are highly desirable, it is long life which is critical to achieving acceptable depreciation costs for propulsion batteries in on-road vehicles.

Total Costs of Stored Electricity

The total costs of stored electricity include both battery depreciation and purchase of recharge electricity. For the near-term batteries projected here, depreciation costs far exceed recharge electricity costs despite assumed cycle lives well beyond those of recent years. Both costs, in cents per kilowatt-hour of battery output, are shown in Table 3.4. Since four-passenger electric cars may require roughly 0.4 kWh of battery output per mile driven, the table implies that total

TABLE 3.4

COST OF ELECTRICITY FROM PROPULSION BATTERIES

Battery Type	Battery Cost, $/kWh	Battery Life, Cycles[1]	Battery Efficiency percent[2]	Costs of Stored Electricity, cents per kilowatt-hour: Recharge Electricity[3]	Costs of Stored Electricity, cents per kilowatt-hour: Battery Depreciation[4]	Costs of Stored Electricity, cents per kilowatt-hour: Total
Golf-Car (1970-1980)	55	250	75	4.0	24.8	28.8
Near-Term (by 1990)						
Lead-Acid	55	800	80	3.8	7.7	11.5
Nickel-Iron	90	600	65	4.6	16.9	21.5
Nickel-Zinc	90	400	75	4.0	25.3	29.3
Zinc-Chlorine	90	1500	55[5]	5.5	6.8	12.2
Advanced (by 2000)						
Zinc-Chlorine	60	2000	60[5]	5.0	3.4	8.4
Lithium-Metal Sulfide	60	1000	70	4.3	6.8	11.0

---

[1] 80 percent depth of discharge.

[2] Charger efficiency not included; assumed to be 90 percent.

[3] Electricity price assumed to be 3 cents per kilowatt-hour, a representative rate for off-peak recharging which is about half the average price for residential electricity in mid-1980.

[4] 10 percent salvage value assumed.

[5] Includes charger/refrigerator.

Source: General Research Corporation

costs for near-term batteries will be roughly 5 to 12 cents per mile, including depreciation, whereas costs of recharge electricity alone would be only 1.5 to 2.2 cents per mile.

Uncertainties

The battery projections and assumptions advanced here are to be viewed with caution. Such projections have usually been over-optimistic in the past. In early 1967, for example, the US Senate Committee on Commerce and Public Works held joint hearings on "Electric Vehicles and Other Alternatives to the Internal Combustion Engine."[8] At the hearings, a procession of experts spoke optimistically about metal-air and sodium-sulfur batteries, which were then in vogue:

> "...zinc-air rechargeable batteries should offer advantages in performance, weight, volume, and material costs...continued development...should lead within the next couple of years to truly economically feasible batteries for electric vehicles." Dr. Stewart M. Chodosh, Battery Manager, Leesona Moos Laboratories.
>
> "In our judgment the zinc-air battery project is well ahead of every other advanced project and stands a good chance of success." Charles Avila, President, Boston Edison Company.
>
> "We are expecting commercial availability of these zinc-air batteries in the early 1970s." Dr. Frederick de Hoffman, Vice-President, General Dynamics.
>
> "We believe that, within the next decade, research and development now being conducted by Ford and others will make it possible to produce marketable electrical vehicles much superior to any that can be built today.
>
> "Our sodium-sulfur battery is now in an advanced stage of laboratory development. Its technical feasibility and excellent performance have been demonstrated..." Michael Ference, Jr., Vice-President, Scientific Research, Ford Motor Company.

Now, however, thirteen years later, neither of these battery systems is commercially available. Moreover, neither is considered a near-term development by the Department of Energy. The sodium-sulfur battery remains among advanced developments which may eventually become available, while zinc-air systems have almost dropped from view, even in the research community.

3.3 DRIVE TRAIN

Background

The electric drive train converts electric power from the battery to mechanical power at the driven wheels of the electric vehicle. Its major components are ordinarily an electric motor, an electrical controller, a transmission, and a differential, as illustrated in Fig. 3.3. The motor converts electrical power to mechanical power. The controller regulates the amount of power flowing from the battery to the motor, and thus the speed and acceleration of the vehicle. The transmission and differential perform the same functions they perform in conventional vehicles: reducing the high rotation speed of the motor shaft to the low rotation speed of the driven wheels, and dividing the mechanical power between the two driven wheels.

Conventional direct-current motors have been used in the great majority of electric vehicles, past and present. Such motors have only a single moving part, a rotating set of electromagnets called the armature. The armature revolves within a stationary set of electromagnets called the field. Electric current flows to the armature through a set of carbon brushes which slide on a segmented copper cylinder called a commutator. The brushes are fixed to the frame of the motor and are motionless, while the commutator is mounted on the armature shaft and rotates with it. The commutator reverses the direction of current flow through the armature magnets at appropriate moments to obtain continuous armature rotation.

The simplicity of the electric motor leads to very high reliability and long life. Only the brushes require periodic maintenance, usually an inspection at intervals of 500 to 1000 hours of operation (a year or two in automotive use) and replacement when required.

Unlike the internal-combustion engine, the electric motor is reversible and self-starting. Furthermore, it develops high torque at zero speed, provides its full rated output with high efficiency over a wide range of speeds, and can deliver two to three times its continuous output rating for short periods of time. All this makes it so well suited to vehicular propulsion that an electric motor of 20-30 horspower rating is the rival of internal combustion engines with much higher ratings, in the 50-75 hp class. The weight of such a motor, roughly 4-5 pounds per horsepower of short-term output capability, falls between that of gasoline engines (3-4 pounds per horsepower) and lightweight diesel engines (5-6 pounds per horsepower). Its cost in mass production would be less than that of either gasoline or diesel engines.

For vehicular use, however, the electric motor is incomplete without an electrical controller to vary its speed and power output in accord with the wishes of the driver. Depending on its design, the controller may be more expensive than the motor, and almost as bulky although lighter in weight.

Early electric vehicles employed large manually-operated rotary switches as controllers. The switches connected the cells of the propulsion battery in different arrangements to change the battery voltage

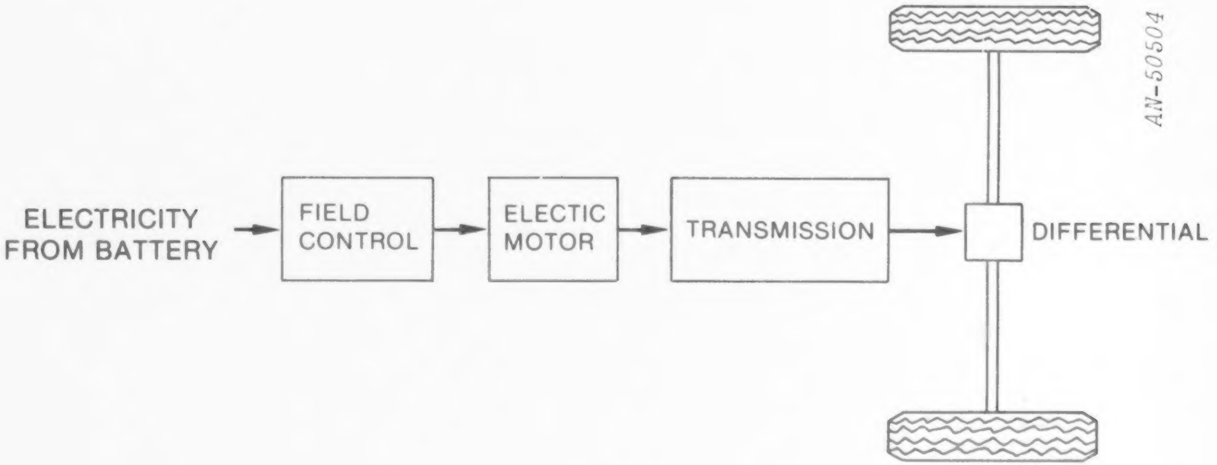

ELECTRICITY FROM BATTERY
FIELD CONTROL
ELECTIC MOTOR
TRANSMISSION
DIFFERENTIAL
AN-50504

Figure 3.3 The Basic Electric Drive Train

applied to the motor, and sometimes included resistors to limit motor current. Only a few selectable levels of power and speed were thus available to the operator. With the substitution of large relays called contactors for the manually-operated switch, this type of controller can be operated by a conventional accelerator pedal. Such contactor controllers are widely used in electric lift trucks, where they have proven inexpensive and reliable.

About twenty years ago the advent of high-power semiconductor switches made a new type of controller possible, the chopper controller. The chopper interrupts the flow of electric current periodically to reduce its average value to a desired level. Semiconductor switching makes this interruption possible at such high rates, hundreds or thousands of times per second, that to the user the flow of power to the electric motor appears smooth and continuous. Choppers capable of handling the full flow of power from battery to motor are large and expensive, but give smooth control of motor speed from its maximum rated speed all the way down to zero. Choppers of much more limited capability are used to control only the current flowing in the motor field winding. They are much smaller and less expensive, but allow motor speed to be varied only through a speed range of perhaps three to one without sacrifice of efficiency. Control does not extend all the way down to zero speed.

Whether they are built with high-power choppers, field choppers, or both, controllers require a main contactor to disconnect the battery entirely when the vehicle is at rest. They ordinarily include sensors to detect overheating of the motor or excessive input currents and some means to reduce power input to the motor to protect it against damage which might otherwise result. Unless reverse movement of the vehicle is accomplished by a transmission, additional contactors may be required to reverse the rotation of the motor. Finally, modern controllers are required to provide regenerative braking, which entails additional circuitry. The conventional electric motor can operate with equal efficiency as a generator, allowing the kinetic energy of a vehicle to be converted to electricity during deceleration rather than lost as heat in ordinary friction brakes. The electricity is returned to the battery, where it is available for subsequent use.

A transmission is ordinarily required to reduce the shaft speed of the electric motor to a level compatible with the lower rotation speed of the driven wheels. Electric motors can be built to run efficiently at very low speeds, but this increases motor weight and cost so much that it is preferable to add a transmission to a higher-speed motor. Multispeed transmissions increase motor speed and efficiency during periods of low driving speed, but some designers have not considered these benefits sufficient to offset the extra expense and operating complexity involved.

A differential is usually included to distribute an even flow of power from the transmission to the two driven wheels of the vehicle. It is made necessary by vehicle turns, which cause the driven wheels to revolve at unequal speeds. A few electric vehicles have dispensed with the differential, substituting instead separate drive motors for the driven wheels. Generally, however, it appears that a single motor with differential is less expensive and equally effective overall.

The objectives of drive train design are to provide adequate propulsive power with high efficiency, high reliability, low weight, and low cost. Existing technology is already close to meeting all these objectives. Efficiency is so high, near 80 percent overall, that little is left to be gained. Motors are already highly reliable and with the experience gained from mass production, controllers will probably become equally reliable. Drivetrain weight is comparable to that of conventional internal-combustion vehicles. Drivetrain cost remains higher than that of conventional vehicles due largely to the cost of the controller, but the differential is far less than that between the costs of the gas tank and the propulsion battery.

In short, the electric drive train is not a major obstacle to successful electric vehicles. Improvements in drivetrains, especially those leading to lower cost, remain desirable, but improvements so great they would offset the drawbacks associated with the propulsion battery do not appear possible.

Examples of the State of the Art

The drive train developed by General Electric for DOE's electric test vehicle ETV-1 is built around a sophisticated chopper controller and a conventional DC motor. Its transmission is a simple chain drive which offers a fixed speed reduction, and its differential is a standard component of the front wheel drive assembly built by Chrysler for its Omni and Horizon models.[4]

The controller employs separate choppers to control motor armature current and motor field current. The armature chopper, a device capable of handling currents as large as 400 amps, controls the motor at vehicle speeds from zero to 30 mph, which correspond to motor speeds from zero to 2500 rpm. At speeds above 30 mph, the armature chopper is bypassed and motor speed is controlled by the field chopper, a much smaller device which supplies currents of 5-10 amps to the field electromagnets. A third chopper unit with 200-amp capability is used to control battery charging current during regenerative braking. The two high-current choppers utilize special high-current transistor modules developed especially for this application. The transistors enable higher chopping frequencies and simpler control circuits than the SCR's (silicon controlled rectifiers) which have been used in most chopper controllers for electric vehicles. The low current chopper is used not only for controlling motor field current, but for controlling battery current (at levels up to 24 amps) during recharging from 120-volt outlets. Overall operation of the controller is directed by a microcomputer.

The DC motor used in the ETV-1 is a conventional design which was tailored specifically for this application (see Fig. 3.4). It is only 17 inches long and 12 inches in diameter, but can provide 20 horsepower continuously at any speed between 2500 and 5000 rpm at an efficiency of almost 90 percent. Operating at this rating, the motor requires an electrical input of 96 volts at 175 amps. For short periods it can be operated at input currents up to 400 amps, with correspondingly higher power outputs. Total motor weight is about 200 pounds.

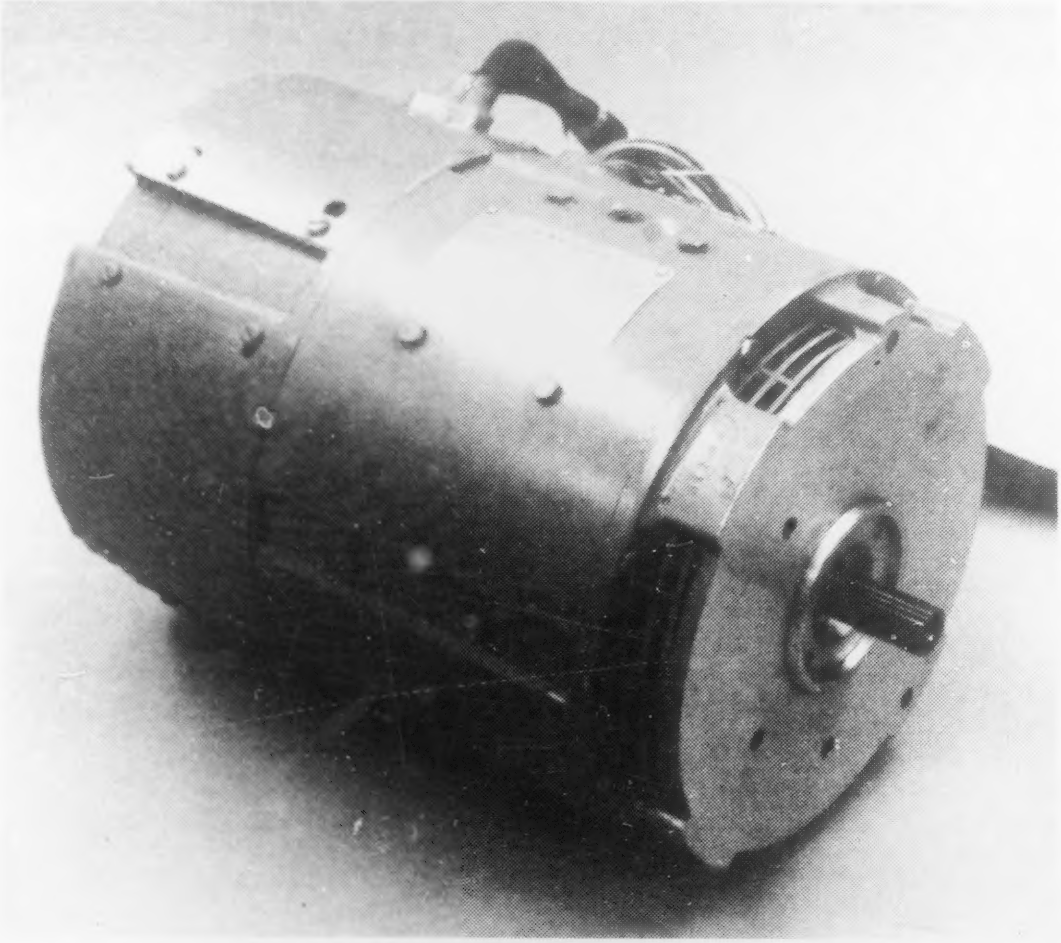


Figure 3.4 The 20-hp DC Motor Developed by General Electric for the DOE Electric Test Vehicle ETV-1

Taken together, the motor and controller would be more expensive than the conventional internal-combustion engine they would replace. In a mass-produced version of the ETV-1, their extra cost would be about $800, as compared with $1470 for the propulsion battery and a total extra cost of about $2900 in relation to the comparable 1980 Dodge subcompact.[9] The cost of the controller would be about equal to that for the motor.

A different approach to drivetrain design is exemplified by the conversion of a conventional ICE car developed by South Coast Technology with support from the Department of Energy.[10] The conversion is based on the Volkswagen Rabbit and utilizes the entire transaxle assembly of the basic car, including the clutch. It adds a conventional DC motor similar to that of the ETV-1, but employs a simple controller which includes only a single inexpensive chopper. The chopper controls only the field current of the motor, and thus varies motor speed only through a range of about 1800-3600 rpm.

Operation of the South Coast car is similar to that of a conventional ICE car with manual transmission. With the transmission in neutral, the operator starts the motor by turning a key similar to an ordinary ignition key. During the second or so required by the motor to reach its minimum speed, a resistor is switched into the circuit by the controller to minimize inrush current. To drive the vehicle, the operator shifts gears and engages the clutch much as in a conventional vehicle. As in the conventional vehicle, the motor "idles" during stops. Resultant loss of energy is small in ordinary driving, where stops are relatively infrequent.

Despite its simplicity, the controller provides regenerative braking. Just as weakening the field current increases power flow to the motor, field strengthening reduces it. The field control can not only reduce motor current to zero, but reverse it. Then the motor acts as a generator, decelerating the car by converting its kinetic energy to electricity flowing back into the battery. Regeneration is only possible, of course, at speeds down to the minimum speed of the motor, but by downshifting regeneration can be achieved at vehicle speeds down to about 10 mph.

The arrangement of the South Coast Rabbit's drivetrain is expeditious for a conversion because it makes maximum use of existing components within the basic car. It also illustrates, however, how effecively mechanical components--the manual multispeed transmission and clutch--may be used to reduce the complexity and cost of the electrical controller, and the cost of the overall vehicle. Despite the extra effort required for their operation, manual transmissions might be prefered by many future buyers of electric cars, just as they are now preferred by an increasing number of buyers of conventional cars.

Future Drivetrains

Drivetrain R&D for electric vehicles is concentrated on the development of improved brushless motors and their associated controllers.[3] Brushes are undesirable because they require maintenance and limit the speed at which the motor can operate. Higher operating speed generally leads to proportionate increases in maximum power output from a motor of given weight. Thus brushless motors might at once require less maintenance and weigh less than conventional designs. Brushless motors may also be substantially cheaper, partly because they weigh less, partly because they are amenable to designs which are especially suited to low-cost, high-volume production.

Brushless motors are of two general types: DC machines with external electronic circuits to replace the commutor and brushes of the conventional design; and AC machines with external electronic circuits to convert the DC output of the battery to the AC power required by the motor. In general, the number of high-power semiconductor devices required for brushless motors exceeds the number required for chopper controllers like that of the ETV-1. Unless lower-cost electronic components and designs can be developed, then, savings in the weight and cost of the brushless motors may be offset by increases in the weight and cost of the electronic controllers they require.

Transmissions for electric drivetrains are most likely to be spin-offs of developments intended primarily for conventional ICE vehicles. Innovations likely to appear soon are the continuously-variable transmission and the automatically-shifted multispeed gearbox.[11] A continuously-variable transmission would relieve the requirements placed on the electric controller for varying motor speed. So would the automatic gearbox, but with higher overall efficiency of operation. With such transmissions, cars with simple and inexpensive controllers like that of the South Coast Rabbit could be satisfactory for many more motorists, including motorists unable to use a manual transmission.

Future motors and controllers may well be no more expensive than the ICE system they supplant. It cannot confidently be predicted yet whether this will come about through improvements in high-power chopper controllers, through the advent of advanced brushless motors, or through the combination of more sophisticated transmissions with a simpler DC motor and field controller designs. It appears, however, that at least one of these developments will succeed.

3.4 VEHICLE DESIGN

Basic Considerations

The major functions of the motor vehicle are to move passengers and other payload swiftly, safely, comfortably, and conveniently, at minimum cost. The major components integrated into an electric passenger vehicle for this purpose include:

- The payload compartment, which provides comfortable seating, shelter from the elements, protection in crashes, space for parcels and luggage, convenient controls for the operator of the vehicle, and such amenities as heating and air conditioning.
- The drive train, which provides propulsive power for acceleration and cruising.
- The battery, which supplies electric energy to the drive train.
- The supporting structure and chassis, including wheels, brakes, suspension, steering, and other items necessary to carry the payload and passenger compartment, the drive train, and the battery on streets and highways.

The components of a conventional ICE vehicle differ only in that the fuel tank supplants the battery, and the drive train includes the ICE system rather than an electric motor and controller. In practice, however, the difference between the weight, bulk, and cost of the gasoline tank and the battery is so great that they become the central problem of electric vehicle design.

In every vehicle design, a basic compromise is struck between capability and cost. In conventional vehicles, extra speed and payload capacity are generally associated with higher cost. In electric vehicles this remains true, but a new dimension is added: driving range.

To increase the range of an electric vehicle with a given battery technology means that the size of the battery must be increased. Since the battery is a major contributor to vehicle weight, the power output and weight of the drive train must be simultaneously increased to avoid reductions in acceleration and top speed. With substantial weight increases in the battery and the drive train, the supporting structure and chassis must also be made heavier. All of this leads to an increased initial price for the long-range vehicle, higher energy use in operation, and increased operating costs.

In the conventional vehicle, the gasoline tank is a very small part of total car weight and cost. Increasing range, payload capacity, or propulsion power is inexpensive because it does not involve proportionate increases in a heavy and expensive propulsion battery. Furthermore, range is less important because refueling can be accomplished in minutes rather than hours.

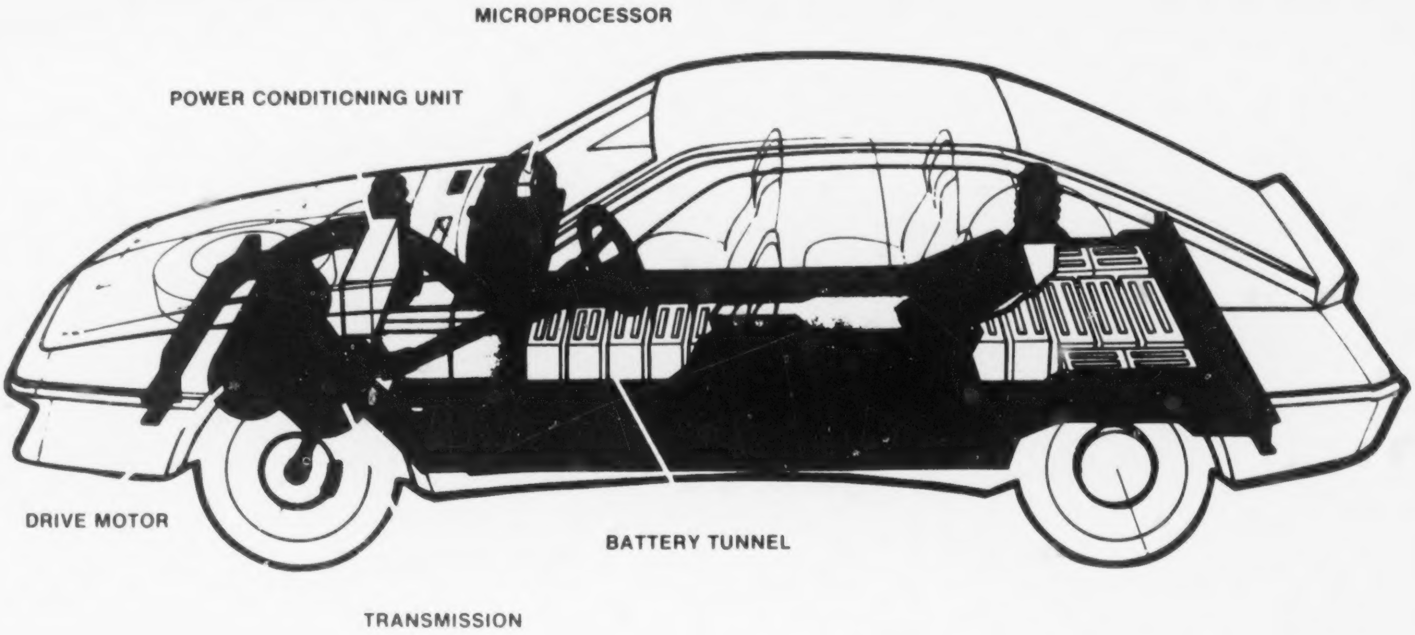
In electric vehicles, the cost of additional payload capability, acceleration capability, and range is so high that it is worthwhile only if frequently used. Accordingly, rear seats, high acceleration, and the maximum feasible ranges with given battery technology are not always offered in electric cars, since auto occupancy is usually only one or two persons, modest acceleration suffices to keep up with almost all traffic, and daily travel by the average automobile in the United States is under 30 miles.

Electric vehicles also tend to be smaller than conventional vehicles because most auto buyers work under budgetary limitations. Buyers who could afford an $8,000 electric subcompact instead of a $5,000 conventional subcompact might not be able to afford a $12,000 standard size electric instead of a $7,500 standard size conventional car.

Because the cost of providing capability is so high in electric vehicles, extraordinary efforts are justified to maximize drive train efficiency and minimize the weight of the vehicle payload compartment, supporting structure and chassis. Expensive lightweight materials, for example, might add more to the price of a conventional car than the value of the gasoline they would save over its life, whereas those same expensive materials might result in lower overall costs for the electric vehicle.

Examples of Electric Vehicle Design

The state of the art in the design of electric passenger cars is illustrated by the electric test vehicle ETV-1 completed in late 1979 by General Electric and Chrysler for the US Department of Energy. The central feature of the ETV-1, shown in Fig. 3.5, is the large propulsion battery.[4] The battery is accommodated in an enlarged central tunnel extending from the rear luggage compartment between the four passenger seats to the front motor compartment, which houses the entire drive train(controller, motor, transmission, and front wheel drive axle). The curb weight of the car is 3,320 pounds, while battery weight is almost 1,100 pounds. Thus the battery weighs about one-third of the total car weight without payload. Nevertheless, range in urban driving is expected to be only 50-75 miles. The ETV-1 is comparable to the Chrysler Horizon and Omni models in overall size and passenger accommodations, but offers about 40 percent less luggage space. It also offers relatively low acceleration capability: 0 to 30 mph in 9 seconds. A motor rated at 20 horsepower (continuous duty) suffices for this and for top speed in excess of 60 mph. To minimize energy use and thus maximize range, the ETV-1 was carefully designed for low aerodynamic drag, which is 30 to 50 percent below that of most other passenger cars on the road. GE and Chrysler have estimated the price of the ETV-1 in mass production (300,000 units per year) would be about $8,500, about 60 percent greater than the price of the comparable 1980 Dodge Omni, $5,200.


MICROPROCESSOR
POWER CONDITIONING UNIT
DRIVE MOTOR
BATTERY TUNNEL
TRANSMISSION

U.S. DEPT. OF ENERGY
Near-Term Electric Vehicle Program
GE/Chrysler Vehicle

Figure 3.5 Schematic of the Electric Test Vehicle ETV-1

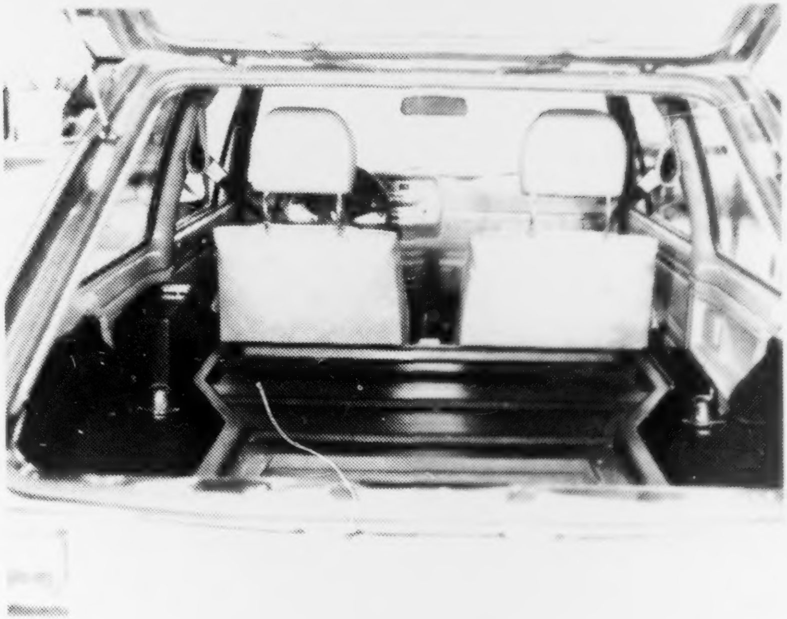
In cars designed from the ground up for electric propulsion, like the ETV-1, designers have maximum freedom in accommodating the heavy, bulky battery and in maximizing range for a given battery size through high efficiency. Most electric vehicles in operation today, however, are conversions of conventional ICE vehicles. In small quantities, conversions are far cheaper than all-new designs. They benefit to the maximum extent from the low cost and proven design built into mass-produced conventional vehicles and their components. The conversions suffer, however, in the compromise necessary to accommodate the weight and bulk of the battery. They also do not benefit from use of the lightweight materials which are not cost-effective for conventional cars (at today's fuel prices) but would be desirable in electric cars.

The state of the art in conversions is illustrated by the electric Rabbit built for the US Department of Energy by South Coast Technology, a small business located in Santa Barbara, California. The battery pack in the conversion consists of 18 golf car batteries, which are the same size as the 18 special batteries included in the ETV-1.[10] To accommodate the battery pack, the rear seat of the Rabbit has been sacrificed, the rear floor modified, and the batteries placed in the area formerly occupied by the rear seat, the gasoline tank, and the spare tire. As shown in Fig. 3.6, the batteries occupy most of the floor space between the front seats and the rear wall of the car. Major modifications were made to the rear suspension of the Rabbit in order to accommodate the extra weight of the batteries, 1,170 pounds. A battery layout like that in the ETV-1 was considered, but rejected because of the much higher costs of the more extensive modifications which would have been required. As in the ETV-1, the entire drive train is in the front engine compartment. The electric motor is mounted on the standard Rabbit transaxle in place of the gasoline or diesel engine, driving the front wheels through the existing clutch and four-speed transmission. Because the motor is smaller than the engine it replaces, there is ample room above it for the controller. In Fig. 3.7, an under-hood view of the converted Rabbit, the controller is the large box slightly to the left of center.

The curb weight of the South Coast Rabbit, 3,120 pounds, is slightly less than that of the ETV-1, but it offers only half the seating capacity. Thirty-seven percent of its curb weight is battery weight. Its acceleration capability (and motor size) are comparable to those of the ETV-1; it achieves zero to 30 mph in about 10 seconds. Its aerodynamic drag is like that of efficient conventional cars now on the road, around 50 percent higher than that of the ETV-1. With golf car batteries, its urban driving range is 35 to 40 miles, whereas the more efficient ETV-1 with its specially-built batteries achieves 50-75 miles.

Method of Projection

With future batteries storing more energy per pound, the range of a car like the ETV-1 could be substantially increased. Alternatively, the car could be designed for a smaller battery at considerably reduced



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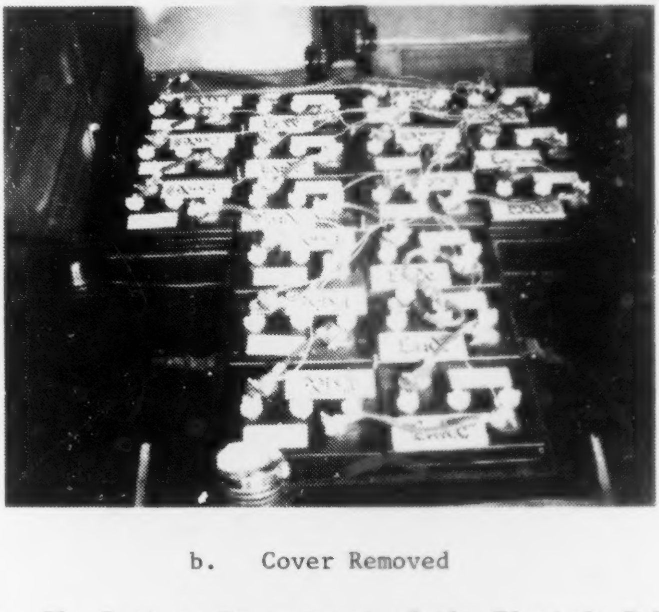

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Figure 3.6 The Battery Compartment of the Electric Rabbit Built by South Coast Technology

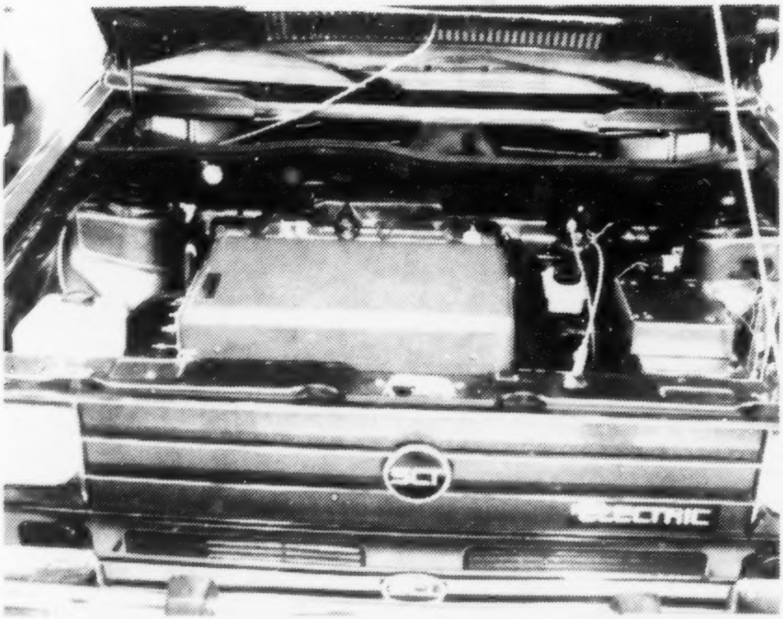


Figure 3.7 The Engine Compartment of the Electric Rabbit

cost. As batteries improve, the spectrum of possible compromises between range and cost will widen, making explicit attention to this possibility more important.

The method of projection used for this report specifically accounts for the spectrum of possible compromises between range and cost. Its results--tradeoffs between range and cost for projected future batteries--are given in the next section. The method is based on four assumptions:

1. Payload and associated passenger compartment weight may be determined from the best current practice in the automobile industry.
2. The weight of supporting structure and chassis will be proportional to the weight of payload, passenger compartment, drive train, and battery. Again, good current practice indicates the constant of proportionality.
3. Drive train weight will be proportional to required power output. Power output, in turn, will be proportional to vehicle weight including a typical payload. Required output will be determined by acceleration requirements.
4. Battery weight will be varied over a range of practical possibility.

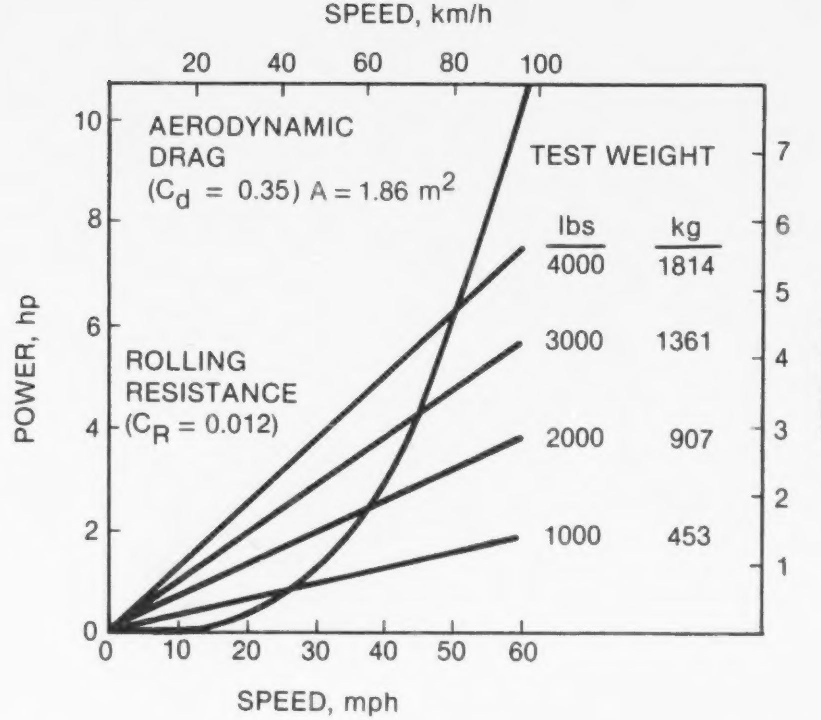
With these assumptions, the weights of the major components of the electric car may be estimated using a simple mathematical model described in the Appendix. The component weights form the basis for estimating initial vehicle price. They also determine total vehicle weight, which is essential for estimating range, energy use, and operating costs. Computer models implementing this approach have been and are being widely used for investigations of future electric vehicles. They are made available by the Cal Tech Jet Propulsion Laboratory, a DOE contractor, on a computer system which is accessible in most cities of the United States.[12]

The third assumption above sizes the drive train of the electric vehicle, and thus its speed and acceleration capability. For projections given here, the drive train was required to produce 28 horsepower of output for each ton of vehicle weight including a standard 300-pound payload. This capability approximately suffices for acceleration of 0-40 mph in 10 seconds on level ground, a capability substantially above that of present electric vehicles such as the ETV-1 and the Rabbit conversion by South Coast Technology. Efficient cars with this capability generally offer top speeds in excess of the 55 mph limit, plus sufficient hill-climbing ability to enter freeways safely from up-hill on-ramps and to maintain safe speeds on most highway grades.

The adequacy of the 28 horsepower per ton drive train requirement follows from the "road load" of an efficient electric car. Road load is the power required to overcome the rolling resistance of a vehicle's tires and wheels, its aerodynamic drag, the force of gravity (while ascending grades), and the inertia of the vehicle during acceleration.

The power required to overcome rolling resistance and aerodynamic drag is modest at legal speeds in comparison with those for climbing grades and for acceleration. The power to overcome rolling resistance is proportional to speed and to vehicle weight. The power to overcome aerodynamic drag rises rapidly at speeds above 30-40 mph (see Fig. 3.8). Depending on vehicle weight, aerodynamic drag will equal tire rolling resistance at speeds in the vicinity of 40-50 mph. For a vehicle weight of about 3,500 pounds during cruise, like that of the ETV-1, the total power requirement at constant speed on a level road would be under 10 horsepower at 45 mph.

Ascending an up-grade at constant speed requires additional power to lift the car. Gradients are usually measured in percent, where a one percent grade corresponds to a one-foot increase in elevation for each hundred feet of travel. Highway gradients, on which safe speeds must be maintained, are usually less than 2 or 3 percent, and on interstate freeways do not exceed 6 percent. The extra power required to overcome each percent of gradient is approximately equal to the power required to overcome tire rolling resistance on level ground. Maintaining 45 mph on



Source: General Research Corporation

Figure 3.8 Road Load for Near-Term Subcompact Cars

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a grade of about 3 percent would increase by a factor of 2 the power requirement for overcoming rolling resistance and aerodynamic drag alone in a typical 3,500-pound vehicle.

Overcoming inertia during acceleration adds even higher power requirements at the acceleration capability assumed here for future vehicles (0-40 mph on level ground in 10 seconds). Computer simulations have shown that this requires about 28 horsepower per ton, or a total of almost 40 horsepower for a 3,500-pound vehicle. This is to be compared with around 10 horsepower for level cruising at 45 mph, and 20 horsepower cruising at the same speed on a 2-1/2 percent gradient. The precise horsepower requirement per ton would vary a little with changes in road load for overcoming tire rolling resistance and aerodynamic drag. The changes are unimportant, however, because most of the power required for the acceleration is used to overcome inertia, not to overcome tire and aerodynamic losses.

Acceleration capability of 0-30 mph in 10 seconds, like that of the ETV-1, is usually adequate for keeping up with traffic. Figure 3.9 shows several measurements of the speed required to keep up with other vehicles in light, moderate, and heavy traffic. Even in light traffic, speed typically reaches 30 mph in about 10 seconds after a stop, and in moderate or heavy traffic even slower increases of speed suffice.

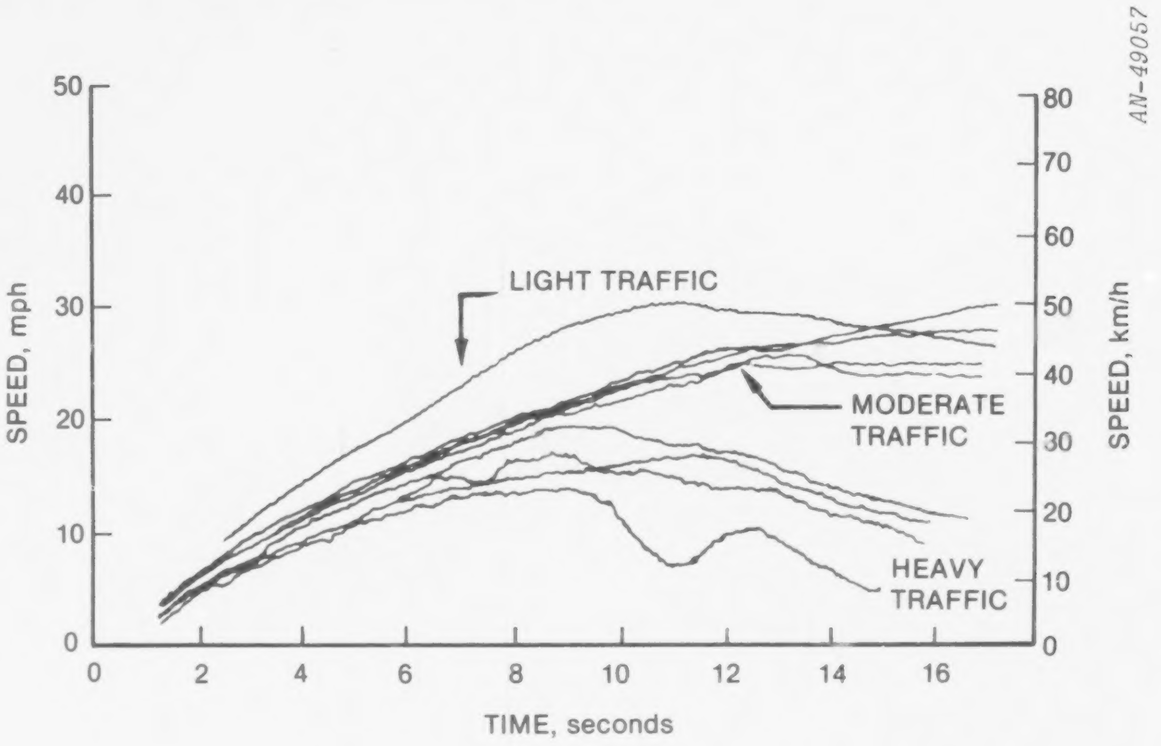
The acceleration requirement of 0-40 mph in 10 seconds used in this report is about the capability of many contemporary diesel cars and low-performance gasoline cars such as VW Beetles. It is based on a consideration of up-hill on-ramps to freeways, which are common.[13] To enter the freeway at a reasonable speed for safe merging with traffic, 40 mph or above, the power requirement for the typical up-hill on-ramp is about the same as that for the 0-40 mph acceleration on level ground in 10 seconds.

Values assumed in this report for rolling resistance and aerodynamic drag are consistent with today's tires and vehicle designs. While bias-ply tires of recent years had rolling resistances of roughly 1.5 percent of the load they carried, radial-ply tires have brought this down to 1.2 percent and below. The figures assumed here, 1.18 percent and 1.08 percent for cars with near-term and advanced batteries, respectively, are to be compared with the value of 1.11 percent for the tires selected for the ETV-1. Aerodynamic drag coefficients of US production cars have usually exceeded 0.5, though increased attention to body design has given the VW Rabbit a drag coefficient of about 0.46 and the new Chevrolet Citation about 0.42. The figure assumed here, 0.35, is better than that of almost any car now in production, but above the 0.30 reported for the ETV-1.

3.5 THE TRADEOFFS BETWEEN RANGE AND COST

The characteristics of future electric vehicles will depend strongly on resolution of a basic tradeoff between range and cost. For a vehicle with given technology, payload, and acceleration capability, both range and cost are determined by the size of battery selected. The larger the battery, the longer the range and the greater the usefulness of the electric car. But a larger battery also is more costly to buy and replace; and its extra weight necessitates increased expenses for a heavier basic vehicle with a more powerful drivetrain.

In the future, the tradeoff between range and cost will be increasingly important because improved batteries will widen the spectrum of possible choices. In the past, there was little freedom of choice about battery size because capabilities of golf-car batteries were so limited. Designers usually put as much battery as possible into their vehicles, often as much as 40 to 50 percent of curb weight, but battery power and energy output remained so low that acceleration and range were inadequate.



Source: D. Gates and M. Pocobello, Electric Van for Metropolitan Service, Paper 730249, Society of Automotive Engineers, Warrendale, Pennsylvania.

Figure 3.9 Measured Acceleration of Urban Traffic

In the future, designers will probably work with batteries providing much higher specific energy and specific power. With more energy and power per pound, the largest possible battery will no longer be required to give reasonable acceleration and range. With a large but still manageable battery, near-term vehicles might achieve twice the range attainable with the minimum battery acceptable from the standpoint of acceleration power. For vehicles with advanced batteries, the maximum design ranges might be three times the minimum, or even more.

These spectrums of future possibilities are examined by using the projection method of Sec. 3.4 to show how sticker price, life-cycle cost, curb weight, and energy use of future electric vehicles might depend on urban driving range. Generally, the projections show that with near-term batteries electric vehicles may offer ranges in excess of 100 miles, or life-cycle costs competitive with those of comparable conventional cars, but not both at once. Vehicles with advanced batteries, however, might simultaneously provide both competitive costs and ranges as great as 200 miles. Neither near-term nor advanced batteries lead to initial prices for electric vehicles competitive with those of gasoline vehicles even at the shortest possible design ranges.

Depending on battery size, projected four-passenger cars with near-term batteries could offer:

- 50-170 mile urban range
- 0.32-0.56 kilowatt-hour-per-mile energy use (input to battery charger)
- \$6,500-\$11,000 sticker prices (in 1980 dollars)
- 20.2-30.8 cents per mile life-cycle costs

The initial and life-cycle costs of the comparable ICE vehicle are projected to be \$4,470 and 21.4 cents per mile. The maximum battery weight assumed for these projections was 36 percent of vehicle test weight. The minimum battery fraction, depending on battery type, was in the range 20-24 percent of vehicle test weight. The lead-acid batteries gave the least range--50 to 100 miles--but also the least life-cycle cost, lower than that of the conventional vehicle for design ranges up to 70 miles. The car with the near-term zinc-chlorine battery gave life-cycle costs close to those of the conventional counterpart at its minimum design range of 95 miles, and at all other ranges up to its 170-mile maximum gave the lowest life-cycle costs of the near-term alternatives.

Depending on battery size, projected four-passenger cars with advanced batteries would offer:

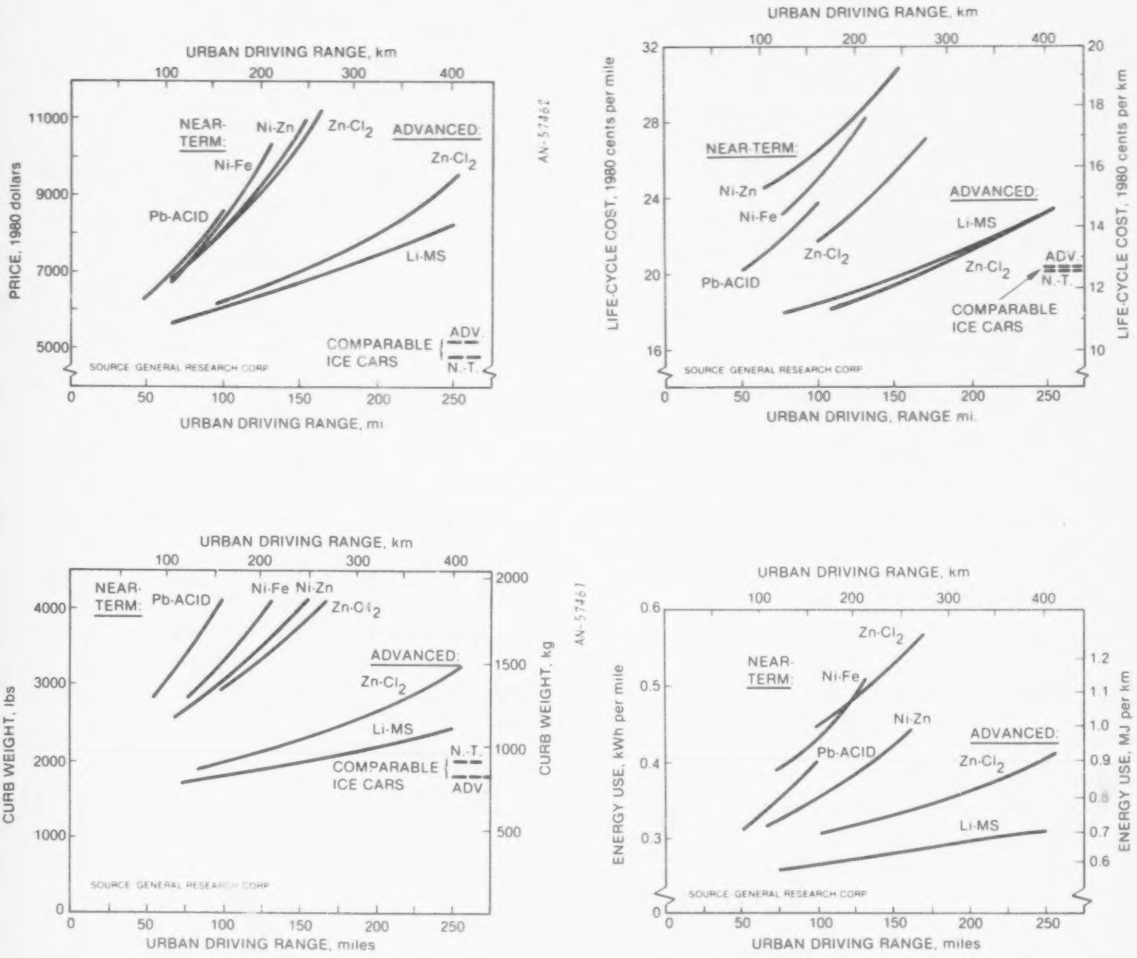
- 65-260-mile urban range
- 0.26-0.41 kilowatt-hours-per-mile energy use (input to battery charger)
- \$5,700-\$9,500 sticker price (in 1980 dollars)
- 17.8-23.5 cents per mile life-cycle costs

The comparable conventional car was projected to offer a sticker price of \$5,140 and a life-cycle cost of 21.7 cents per mile. At all design ranges, the sticker prices of the advanced electric cars exceed this price, but their life-cycle costs are less at ranges up to roughly 200 miles. Battery sizes for the advanced zinc-chlorine car ranged from 17 to 35 percent of curb weight. For the car with the very high-power, high-energy advanced lithium-metal sulfide battery, battery fractions ranged from about 9 to 25 percent. The initial cost of the comparable advanced ICE car is higher than that of the near-term ICE car because it incorporates expensive lightweight materials. The life-cycle cost of this car is also higher than that of the near-term car; gasoline savings provided by its higher fuel economy are insufficient to offset the extra depreciation costs due to its higher-cost, lighter-weight construction (see Fig. 3.10).

The uncertainties in these projections are greatest for the cars with advanced batteries. On the one hand, advanced batteries might be developed earlier than projected here, during the 1980's; on the other, they may not be successfully developed until the next century, if ever. When they do reach mass production, they may well have lesser capabilities, higher prices, and shorter useful lifetimes than those assumed for these projections.

The projections are less uncertain for cars with near-term batteries. It appears likely that at least one of the near-term battery developments will be successful. Which one, however, is less clear; it may not be the one offering lowest cost or highest performance.

The projections for the comparable ICE vehicles are also uncertain. Projected life-cycle costs are based on 1980 gasoline prices (\$1.25 per gallon) even though substantial increases in real gasoline prices are probable for the future. An increase of \$1.25 in gasoline price per gallon (to a total of \$2.50) would add four cents per mile to the life-cycle costs for the comparable ICE cars. Each additional \$1.25 increase would add another four cents per mile. Furthermore, assumed advances in ICE car technology are very modest; they do not include turbo-charged diesel engines, engine restart systems which eliminate



Assumptions:	Mid-1980 dollars
	Acceleration Capability: 0-40 mph in 10 seconds
	Driving Cycle: SAE J227a, Schedule D

Source: General Research Corporation

Figure 3.10 Design Tradeoffs for Four-Passenger Electric Cars

idling during stops, continuously variable transmissions, Brayton or Stirling cycle engines, or any of the other innovations which may substantially reduce fuel consumption and life-cycle costs (though they generally increase sticker prices). Other advances may also be achieved, such as lower-loss tires or lighter structures, but these tend to benefit electric and conventional vehicles equally.

3.6 REPRESENTATIVE FUTURE ELECTRIC VEHICLES

Though short-range electric vehicles are cheapest to own and operate, many motorists will probably prefer the extra utility afforded by longer range, despite the extra cost. If electric vehicles are marketed in large quantities, competing models will probably offer a variety of ranges.

In this section, several representative future electric cars are selected from the spectrum of possibilities developed in Sec. 3.5, for more detailed description and for subsequent use in estimating impacts of wide scale vehicle electrification.

For near-term vehicles, 100 miles appears to be a representative future range capability. This is the adopted goal of DOE development programs for the late 1980's, and has also been stated as a goal in GM's announcements about its electric car development efforts. It is further supported by market data to be discussed in Chapter 6, which indicates that the average motorist purchasing an electric car for urban use as a second car would prefer an urban range capability of 85-95 miles, given the tradeoffs between range and price projected in Sec. 3.5. For other applications, which involve more long-distance driving, more range would probably be desired.

For near-term four-passenger cars with 100-mile range:

- Sticker price would be $8,100-8,500, 75-80 percent greater than the $4,740 price of the competitive ICE car.
- Life-cycle cost would be 22.0-26.6 cents per mile, versus 21.4 cents per mile for the comparable ICE car.
- Electricity input to the battery charger would be 0.4-0.45 kilowatt hours per mile.

For the electric vehicle with advanced batteries, more range would be appropriate because it entails less expense than in the near-term car. For cars with a given range, an advanced battery can be lighter and less expensive than any of the near-term batteries. Increasing battery size (and car range) by a given amount is therefore less expensive for the advanced-battery car, because a smaller portion of its total cost is affected. One hundred-fifty miles appears to be a reasonable expectation for the representative car with advanced batteries. Preferred ranges of 125-150 miles are indicated by the market data in Chapter 6, given the range-versus-cost tradeoffs of Sec. 3.5.

For advanced four-passenger electric cars with 150-mile range:

- Sticker price would be $6,800-7,050, 32-37 percent above the $5,140 price of the comparable ICE car.
- Life-cycle cost would be 19.4-20.1 cents per mile, 8-11 percent lower than the 21.8 cents per mile projected for the comparable ICE car.
- Electricity input to the battery charger would be about 0.3 kilowatt-hours per mile.

Further details of these representative near-term and advanced cars are given in Table 3.5.

The basic factors behind the higher sticker price of the representative electric cars are the weight and cost of the battery, which far exceed the weight and cost of the gasoline tank they supplant. The contribution of battery weight to vehicle weight is illustrated in Fig. 3.11 for the lightest and heaviest of the representative near-term electric cars. For comparison, weight is also shown for the comparable ICE car. Battery weight is the major contributor to the extra weight of the electric cars. Moreover, the extra structure and chassis weight required to carry the weight of the battery also contributes significantly to the total extra weight of the electric cars. For the cars with the nickel-zinc and zinc-chlorine batteries, for example, extra structure and chassis weight is about 250 lbs. Both battery and extra structure contribute to the extra initial costs of the electric vehicle.

More details of the projected initial and life-cycle costs of representative future cars are presented in Table 3.6. The major differences between the electric cars and the comparable ICE cars included in the tables are:

- Cost of the battery and replacements, which add far more to initial and life-cycle costs than those of the gasoline tank.
- Cost of capital, which is higher for the electric car because of the higher initial price and the higher average value of the electric car through its life.
- Costs of repairs and maintenance, which are projected to be much less for the electric vehicles.
- Costs of energy, which for the electric vehicles are about half as much per mile as for the comparable ICE vehicles.

TABLE 3.5

REPRESENTATIVE FUTURE ELECTRIC CARS

	ETV-1 (1980)	Near-Term (by 1990)					Advanced (by 2000)		
Battery Type	Pb-Acid (lead-acid)	Pb-Acid (lead-acid)	Ni-Fe (nickel-iron)	Ni-Zn (nickel-zinc)	Zn-Cl$_2$ (zinc-chlorine)	(ICE)*	Zn-Cl$_2$ (zinc-chlorine)	Li-MS (lithium-metal sulfide)	(ICE)*
Battery Specific Energy, Wh/lb†	16.9	22.7	27.2	31.8	34.0	--	45.4	68.0	--
Nominal Range (urban), mi	60	100	100	100	100	--	150	150	--
Curb Weight, lb	3260	4090	3290	3030	2960	2010	2300	2260	1810
Battery System Weight, lb	1140	1580	1050	890	840	--	600	400	--
Sticker Price, mid-1980 dollars	8480	8520	8400	8130	8120	4740	7050	6810	5140
Life-Cycle Cost, 1980 cents/mi	26.1	23.9	24.9	26.6	22.0	21.4	19.4	20.1	21.8
Electricity Use, kWh/mi	0.38	0.40	0.44	0.38	0.45	--	0.31	0.30	--
Fuel Economy, mpg (urban driving)	--	--	--	--	--	33.0	--	--	35.6

Assumptions:

Electricity Price	$0.03 per kilowatt-hour
Gasoline Price	$1.25 per gallon
Electric Vehicle Life	12 years
ICE Vehicle Life	10 years
Annual Travel	10,000 miles
Urban Driving Cycle	SAE J227a, Schedule D, for electric cars, Federal Urban Driving Cycle for ICE cars
Acceleration Capability	0-40 mph in 10 seconds
Passenger Capacity	Four persons plus luggage

Source:

General Research Corporation. Performance and cost estimates for all vehicles were made with the ELVEC and EVWAC computer models. Costs are in mid-1980 dollars and are based on mass production of all vehicles (300,000 units or more per year).

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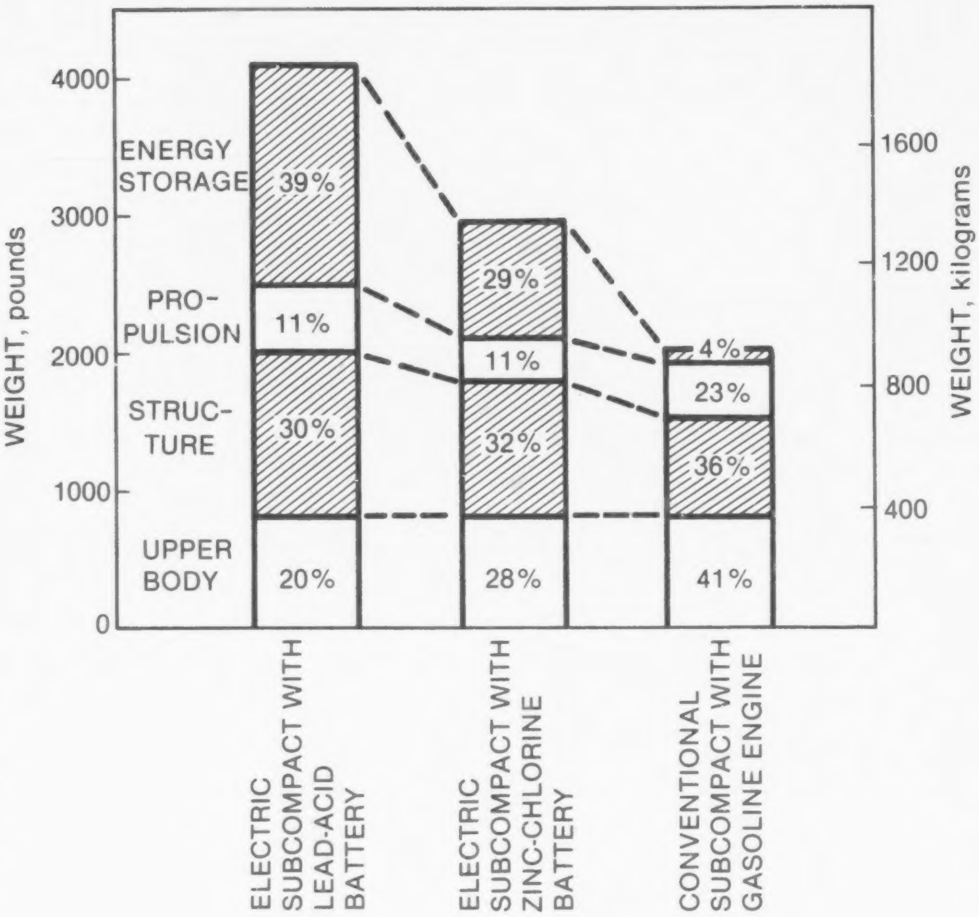
*Internal combustion engine

†Energy delivered by the battery in a full discharge over three hours, in watt-hours per pound of battery weight



Source: General Research Corporation

Figure 3.11 Weight Breakdowns for Representative Near-Term Four-Passenger Cars

TABLE 3.6

INITIAL AND LIFE-CYCLE COSTS OF REPRESENTATIVE FOUR-PASSENGER ELECTRIC CARS

	Near-Term					Advanced		
	Pb-Acid	Ni-Fe	Ni-Zn	$Zn-CL_2$	(ICE)	$Zn-CL_2$	Li-MS	(ICE)
Initial Cost, dollars	8520	8400	8130	8120	4740	7050	6810	5140
Vehicle	6660	5950	5720	5540	4740	5410	5180	5140
Battery	1860	2450	2410	2580	-	1640	1630	-
Life-Cycle Cost, cents per mi	23.9	24.9	26.6	22.0	21.4	19.4	20.1	21.8
Vehicle	5.0	4.5	4.3	4.2	4.3	4.1	3.9	4.7
Battery	3.0	4.8	7.0	2.3	-	1.4	2.6	-
Repairs and Maintenance	1.5	1.5	1.5	1.5	3.9	1.5	1.5	3.9
Replacement Tires	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4
Insurance	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Garaging, Parking, Tolls, etc.	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Title, License, Registration, etc.	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5
Electricity	2.3	2.2	2.0	2.2	-	1.7	1.5	-
Fuel and Oil	-	-	-	-	4.0	-	-	3.7
Cost of Capital	5.5	5.5	5.4	5.4	3.0	4.5	4.4	3.3

All costs are in mid-1980 dollars.

Assumptions:

Electricity Price	$0.03 per kilowatt-hour
Gasoline Price	$1.25 per gallon
Electric Vehicle Life	12 years
ICE Vehicle Life	10 years
Annual Travel	10,000 miles
Car and Battery Salvage Value	10 percent
Cost of Capital	10 percent per year

Car and battery purchases are 100 percent financed over their useful lives.

Electricity cost includes a road use tax equal to that paid by typical gasoline vehicles of equal weight via state and federal gasoline taxes.

Source:

General Research Corporation. Cost categories and many entries, such as tires, insurance, garaging, etc., are based on periodic cost analyses by the Department of Transportation (see Ref. 14). All costs shown were computed by the Electric Vehicle Weight and Cost Model (EVWAC), Ref. 15.

The savings on repair and maintenance are based on data showing that the ICE system in conventional cars has accounted for some 60 to 70[15] percent of all labor hours and parts sales for repair and maintenance. For electric motor-controller systems, which have many fewer moving parts and components with much longer lives, it was assumed that very little service would be required. The same assumption was extended to the propulsion battery, though there is little relevant experience. Especially for battery types which have not been in service, reliability is uncertain. It is also possible that maintenance costs for future ICE cars will be considerably reduced, despite complex pollution controls, by electronic ignition and control systems, long-life spark plugs, tamper-proof controls, and improved quality control.

The fuel prices for the projected ICE cars are 4 cents per mile at the mid-1980 price of gasoline ($1.25 per gallon). Each rise of $1.25 per gallon adds 4 cents per mile to the ICE life-cycle cost projections. Major shifts in relative attractiveness of electric and conventional cars could result from gasoline price increases. For the projected life-cycle costs of conventional cars to equal the life-cycle costs projected for the near-term representative electric cars, these price increases for gasoline would be required:[16]

- 63 percent for lead-acid battery cars (to $2.05 per gallon)
- 88 percent for nickel-iron battery cars (to $2.35 per gallon)
- 105 percent for nickel-zinc cars (to $2.55 per gallon)
- 15 percent for zinc-chlorine cars (to $1.44 per gallon)

The percentage increases required to equalize costs are very sensitive to details of projected battery life and cost. The individual figures given above are uncertain; but overall, it appears likely that price increases for gasoline of 75 to 100 percent are probably required to raise life-cycle costs of comparable ICE cars to equal those of future cars with near-term batteries.

It is noteworthy that the advanced cars are projected to be cheaper on a life-cycle basis than the comparable ICE cars (Table 2.6) despite the assumption of low 1980 gasoline prices. This is the result of the low weight, long life, and modest cost projected for the advanced batteries. Even if these projections materialize, however, lower operating costs may seem unimportant to many motorists in relation to the 35 percent higher sticker prices and the range limitation (assuming gasoline is readily available).

If petroleum alone were used to generate recharge energy, the energy requirements of the near-term electric cars would be equivalent to those of conventional cars getting 26 to 30 mpg (miles per gallon) in urban driving. The advanced-battery cars would increase this equivalent fuel economy to 37 to 38 mpg. This is no more than competitive with the projected conventional cars offering the same passenger space and acceleration, built with the same materials, using conventional ICE drivetrains, which might get 33 to 36 mpg in urban driving. If coal alone were used to generate electricity and produce synthetic gasoline, however, the near-term electric cars would offer the equivalent of 44 to 50 mpg, and the advanced battery cars 64 to 67 mpg. This results from the inefficiencies of using coal rather than petroleum to produce gasoline. Table 3.7 summarizes these projections.

The "comparable ICE cars" discussed here do not necessarily exhibit the ultimate or even likely future potential of ICE propulsion, a subject beyond the scope of this analysis. Instead, they are included only to show how conventional automotive technology of the 1980's might compare with the electric vehicles projected here, assuming both offer the same passenger accommodations and acceleration capability. More advanced technology may lead to much higher fuel economies than the 33-36 mpg projected here. Some possible innovations (much improved tires, aerodynamics, and structures) would benefit both electric and ICE vehicles. Others, notably lighter, more efficient ICEs and continuously variable transmissions, could improve considerably the desirability of ICE vehicles relative to electric vehicles.

In an electric vehicle, around 40 percent of the energy input to the battery charger may be used to overcome road load, as illustrated in Fig. 3.12. On the other hand, the electric energy input to the charger represents only 28 to 30 percent of the energy available from the combustion of the fossil fuels used to produce it. In an ICE vehicle the situation is reversed: petroleum is refined and delivered to the gasoline tank with high efficiency, but in the internal combustion engine which uses gasoline, efficiency in urban driving may be only 10 to 20 percent.[17,18]

Use of regenerative braking in electric vehicles can greatly reduce losses which would otherwise appear in friction brakes, even though friction braking must still be included (Fig. 3.12). For safe and predictable braking, regeneration alone is unsatisfactory because it is effective only on the driven wheels, front or rear, rather than all four wheels. Without regeneration, the 100-mile range of the car described in Fig. 3.12 would be reduced to about 81 miles.

So far, all ranges and energy uses which have been projected here for future electric vehicles are nominal design values: they would be achieved only with a battery in good condition (during perhaps the first two-thirds of its useful life), and only in the given urban driving schedule, on level roads without winds. Near the end of battery life,

TABLE 3.7

EQUIVALENT FUEL ECONOMIES OF FOUR-PASSENGER ELECTRIC CARS RECHARGED FROM PETROLEUM OR COAL RESOURCES

	Equivalent Miles per Gallon*	
Near-Term Cars	Oil	Coal
Lead-acid	29	50
Nickel-iron	26	45
Nickel-zinc	30	53
Zinc-chlorine	26	44
(Comparable ICE car)†	(33.0)	(33.0)
Advanced Cars		
Zinc-chlorine	37	64
Lithium-metal sulfide	38	67
(Comparable ICE car)†	(35.6)	(35.6)

Assumed Conversion Efficiencies (taken from Ref. 16):

Crude oil to gasoline	89 percent
Crude oil to electricity	28 percent
Coal to gasoline	55 percent
Coal to electricity	30 percent

Efficiencies include losses and energy inputs in extraction of the energy resource from the ground, transportation and conversion to its fixed form for vehicular use, and delivery to the vehicle.

Source: General Research Corporation

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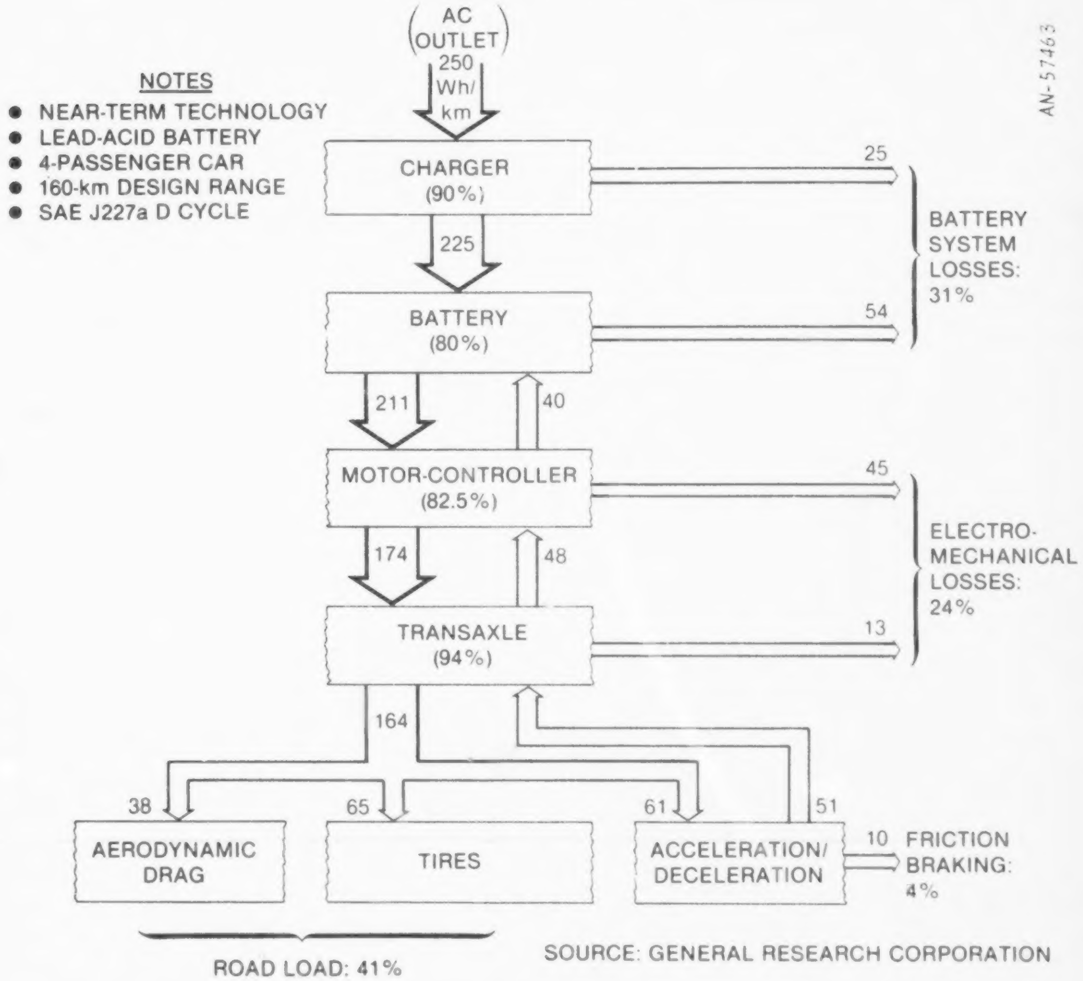
[*] Equivalent miles per gallon is the urban fuel economy of an ICE car requiring the same use of petroleum (for gasoline) or coal (for synthetic gasoline) as would be needed to generate recharge electricity for the electric car.

[†] The comparable ICE cars offer the same passenger compartments and acceleration capability as their electric counterparts, are built with the same materials, and use conventional ICE drive trains. Their fuel economies are projected for urban driving.


AN-57463
NOTES
NEAR-TERM TECHNOLOGY
LEAD-ACID BATTERY
4-PASSENGER CAR
160-km DESIGN RANGE
SAE J227a D CYCLE
AC OUTLET
250 Wh/km
CHARGER (90%)
25
225
BATTERY (80%)
54
BATTERY SYSTEM LOSSES: 31%
211
40
MOTOR-CONTROLLER (82.5%)
45
174
48
TRANSAXLE (94%)
13
ELECTRO-MECHANICAL LOSSES: 24%
164
38
65
61
51
AERODYNAMIC DRAG
TIRES
ACCELERATION/ DECELERATION
10
FRICTION BRAKING: 4%
ROAD LOAD: 41%

SOURCE: GENERAL RESEARCH CORPORATION

Source: General Research Corporation

Figure 3.12 Energy Use in Urban Driving (in Watt-Hours per Mile, with Component Efficiencies in Parentheses)

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range in nominal urban driving would be reduced up to 20 percent. Non-nominal driving conditions, furthermore, can considerably affect the range and energy use. On the one hand, range in the Federal Urban Driving Cycle, range in the Federal Highway Cycle, range in the nominal urban driving cycle, and range at a constant speed of 55-60 mph are all quite close together. On the other hand, changes in battery temperature can affect range by a factor of two; low constant speeds in highway driving can more than double range; 15-mph headwinds or tailwinds in 55-mph highway driving can decrease range some 20 percent or increase it 60 percent; and on long upgrades range can be sharply reduced. Energy use varies almost as widely. This is summarized in Table 3.8.

TABLE 3.8

EFFECT ON RANGE OF CHANGED DRIVING CONDITIONS

Driving Condition	Range, mi	Energy Use, kWh/mi
Urban Driving		
SAE J227a, Schedule D	100	0.40
Federal Urban Driving Cycle	113	0.37
Battery Temperature = 32°F	65	-
Battery Temperature = 100°F	123	-
Highway Driving		
Federal Highway Cycle	106	0.38
Constant 60 mph	98	0.41
Constant 50 mph	133	0.34
Constant 40 mph	179	0.29
Constant 30 mph	235	0.24
Constant 55 mph	115	0.38
with 15 mph headwind	79	0.50
with 15 mph tailwind	164	0.29
on 3 percent upgrade	37	0.85

Source: General Research Corporation

All ranges estimated by the ELVEC simulation for a four-passenger car with near-term lead-acid battery and design range of 100 miles.

The nominal driving schedule used to estimate design range, Schedule D of SAE Recommended Procedure J227a, is the most demanding of four schedules recommended by the Society of Automotive Engineers for electric vehicle testing. Each cycle of the schedule requires 122 seconds and traverses about 0.95 mile. Starting from rest, the cycle requires a 28-second acceleration to 45 mpg, a 50-second constant speed cruise, a 10-second coast, and a 9-second braking to zero mph, followed by a stop. The Federal Urban Driving Cycle used for evaluating pollutant emissions and fuel economy of conventional cars is far more complex. It lasts 1372 seconds and is based on actual records of vehicle operation in an urban area, both on city streets and on a freeway. It remains to be determined which of these cycles is the better indicator of actual EV range and energy use in average urban driving.

Battery temperature can have a major effect on battery output and vehicle range. Available battery capacity may change as much as 6 percent for a 10°F change in battery temperature, depending on battery design and on initial battery temperature.[19] The results in Table 3.8 are based on this high assumed sensitivity to temperature, and may represent upper bounds on the magnitude of likely range changes in the future. Insufficient data was available to estimate associated changes in energy use. Because of this potential sensitivity, batteries in electric vehicles for cold climates are very likely to be housed in insulated compartments, with heating available from the source of recharge power. In ordinary operation a considerable amount of energy is lost as heat in the battery. Supplemental heat from an external source will probably be necessary only for cars left idle for long periods, or in very cold weather. The electrolyte of a discharged battery freezes at temperatures well above 0°F, a condition which must be avoided to avoid battery damage. High electrolyte temperatures must also be avoided; they reduce battery life.

In highway driving near 55 mph, electric car ranges are typically like those attained in nominal urban driving. The effects of lower speeds on highway range can be dramatic, however, as can the effects of winds. A 3-percent grade affects range even more drastically. The case in Table 3.8 is extreme because a 3-percent grade 37 miles long implies a total ascent of almost 5900 feet. Though freeway grades are occasionally steeper (up to 6 percent), they are very seldom long enough to involve so great a change of elevation.

Heating and cooling of passenger compartments pose special problems for electric vehicles. ICE vehicles utilize waste engine heat, which is sufficient for passenger comfort in all but the coldest climates, where an auxiliary gasoline heater is often added. Electric drive is so efficient, however, that relatively little waste heat is available. Wider use of auxiliary gasoline heaters would be one possible remedy. Another would be efficient use of electric heating, which might be used to heat occupied seats directly rather than the entire car interior. Alternatively, a heat pump might be employed. Since a heat pump is reversible, it could also act as an air conditioner to provide cooling on hot days. Full-time use of an air conditioner or heat pump with the capacity typical for conventional vehicles would reduce the range of an electric vehicle roughly 15 percent. On most days, of course, this would be acceptable since the full 100-mile range would be required relatively infrequently.

So far, comparisons between representative future electric and ICE vehicles have been limited to the case of four-passenger cars. Generally, however, the comparisons remain valid for larger cars and for light trucks (pickups and vans). For example, the sticker price of the four-passenger car with zinc-chlorine battery was 71 percent above the sticker price of the comparable ICE car (Table 3.5). The sticker price of the five-passenger version of this car is also 71 percent higher than that of the comparable five-passenger ICE car. Within a few percentage points, similar car comparisons also hold true for other key vehicle characteristics such as curb weight, life-cycle cost, and energy use, and for other vehicle sizes and types. A complete set of descriptors for comparable zinc-chlorine EVs and comparable ICE vehicles is given in Table 3.9. These and similar projections for EVs with other batteries demonstrate that comparisons drawn between four-passenger electric and ICE cars generally prevail for the other vehicles as well.

Under detailed examination, electric light trucks compare a little less favorably to their ICE counterparts than do electric four-passenger cars. Here, as in the four-passenger car, a 300-pound payload was assumed throughout. Had the light trucks been loaded to their maximum design payload of 1190 pounds, the electric trucks would have compared even less favorably to the ICE trucks because their range would be substantially reduced. The range of the ICE trucks is similarly reduced by loading, but shorter range is less important for ICE trucks because refueling is so much faster.

It is possible that small, low-performance two-passenger cars may play a significant role in future urban travel. At present, little more than 1 percent of cars sold in the US seat only two passengers, and most of them are sold as sport cars for high performance. Drastic changes in gasoline price and availability, far exceeding those of the 1970's, would probably be required to effect a major market shift to low-performance two-passenger cars. Should this happen, however, there is no reason to expect that electric cars built with the technology described here would gain any relative advantage in price or capability over ICE cars of this same small size. Like the larger electric cars, two-passenger electrics would be 70 to 80 percent more expensive to buy, and equally limited in range.

TABLE 3.9

CHARACTERISTICS OF LARGER VEHICLES RELATIVE TO THOSE OF REPRESENTATIVE FOUR-PASSENGER CARS

	Near-Term Vehicles With Zinc-Chlorine Battery				Comparable Near-Term ICE Vehicles			
	Curb Weight, lb	Sticker Price, dollars	Life-Cycle Cost, cents/mi	Fuel Use, kWh/mi	Curb Weight, lb	Sticker Price, dollars	Life-Cycle Cost, cents/mi	Fuel Economy, mpg
4-Passenger Car	2960	8120	22.0	0.45	2010	4740	21.4	33.0
5-Passenger Car	3430	8490	24.7	0.51	2300	5540	23.7	30.0
6-Passenger Car	4270	12760	30.6	0.61	2900	7870	29.5	25.0
Compact Pickup	3360	8570	23.0	0.52	2164	4690	21.6	31.0
Compact Van	3700	9520	24.7	0.61	2330	5080	22.9	27.0

Assumptions:

- 1980 dollars
- 100-mile electric vehicle range (with 300-lb payload, in urban driving)
- Acceleration capability 0-40 mph in 10 seconds for electric and ICE vehicles

Source:

General Research Corporation

Two-passenger electric cars may nevertheless play a prominent role among the first electric cars to come to market. So long as electric cars are purchased by only a few percent of motorists, who will probably differ sharply from the average motorist, a large proportion may be two-passenger cars. The first GM electric car may well offer only two seats--but it needs to appeal to only 2 to 3 percent of new car buyers in order to succeed.

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4 HYBRID VEHICLE SYSTEMS

4.1 INTRODUCTION AND SUMMARY

A hybrid-electric vehicle includes an internal combustion engine in addition to an electric propulsion motor and storage battery. There are many workable arrangements for sharing propulsion duties between engine and motor, giving rise to a broad spectrum of possible hybrids. At one end of this spectrum are hybrids much like pure EVs; they usually operate all-electrically, derive most of their energy from electric utilities, and employ their ICEs only to extend range on long trips. At the other end of the spectrum are hybrids much like pure ICE vehicles; they derive all their energy from gasoline and employ their electric components simply to increase the average efficiency and reduce the average emissions of their ICEs. In between are vehicles with many of the advantages, and disadvantages, of both electric and ICE propulsion.

Hybrids were conceived long ago in attempts to combine the best attributes of both electric and ICE propulsion. A patent granted in 1905, in fact, diagrams the hybrid configuration which today enjoys greatest popularity.[1] A few hybrids were built and sold in the United States after 1910, but the combination of ICE, electric motor, and battery which eventually captured the entire motor vehicle market made no direct use of the electric motor for propulsion. Instead, the battery and motor were employed only to start the ICE, as Charles Kettering's "self-starter" for the 1912 Cadillac. For most of the years since, market forces have favored no larger role for the electric motor and battery in motor vehicles.

Interest in hybrids was reawakened in the 1960s, when worsening air pollution forced a major reevaluation of the use of ICEs for vehicular propulsion. The resultant consensus, however, was that hybrids were complex and costly. In 1967, a panel of experts convened by the Department of Commerce to investigate electrically-powered vehicles dismissed hybrids in a single paragraph as economically uncompetitive.[2] It is worth noting that the panel dismissed its assigned topic, electric vehicles, almost as briefly, and then went on with incisive foresight and broadened scope to recommend what has since come to pass (national air quality and emission standards, clean-up of conventional vehicles).

Hybrid R&D continued nevertheless with both government and industry sponsorship, and after 1973 its objectives shifted increasingly to conservation of petroleum. In 1976 an experimental program at Ford Motor Company showed potential fuel economy improvements of 30 to 100 percent with a hybrid configuration resembling a conventional ICE system with a much enlarged starter motor.[3] The electric motor was used for all vehicle movement up to 10 to 15 mph, not just to start the ICE; but because all battery recharge came from regenerative braking or the ICE, no use was made of electric utility power. Also in 1976, a small business described a hybrid with a larger electric motor which was used more extensively to assist a small ICE in propelling the vehicle.[1] In this hybrid, recharge energy from electric utilities was deliberately used to supplant gasoline use.

Today, hybrid R&D is aimed at use of electric energy from utilities and at vehicles with sufficient all-electric capability to remain operable even in the complete absence of gasoline. Because of the resultant emphasis on electricity stored in batteries, these hybrids are nearly as dependent as pure electric vehicles on improved batteries with more energy per pound and much longer life. They also require most or all of the electric drive train components of the electric vehicle. Probably because of these factors, most developers have focused on the pure electric vehicle, postponing the hybrid (with the complication of its added ICE) until satisfactory electric vehicles become available as a starting point.

Despite their slower start in R&D, hybrids ultimately may prove superior to pure electric vehicles for many motorists. The ICE effectively can relieve the range limitation of the pure electric car, or raise its acceleration to equal that of ICE cars, or both. Yet the hybrid can simultaneously be no more expensive, and retain some or all of the electric vehicle's capability to electrify travel with energy from electric utilities.

A "range-extension" hybrid with almost all the desirable properties of the pure electric vehicle is derived from the all-electric vehicle by substituting a small ICE for part of the propulsion battery. The ICE is just large enough to power continuous cruising on the highway (15-25 hp). For simplicity and efficiency, it has a direct mechanical connection to the electric motor shaft. The ICE operates only for extended highway travel. In urban driving, it is disconnected and the vehicle operates electrically. This arrangement not only eliminates the range limitation which is the principal disadvantage of the electric car, but is also among the simplest of the hybrid configurations to build. In addition, it minimizes problems of controlling air pollutant and noise emissions, because the ICE would operate very little in urban areas.

With a useful electric range of 60 miles, the future range-extension hybrid could electrify about as much of the travel of a typical US auto as the pure electric car with 100-mile maximum range. Yet the hybrid could be both lighter and cheaper, with unlimited driving range on its ICE. Projected sticker prices for such hybrids using near-term lead-acid and nickel-zinc batteries are $7,700 and $8,000, about 5 percent under those of comparable electric cars (though still 65 to 70 percent above those of comparable ICE cars). Projected life-cycle costs for these hybrids are 23.5 and 26.0 cents per mile, 2 percent under those of the electric versions (but 10 to 20 percent above those of the comparable ICE cars).

With the advanced lithium-metal sulfide battery and a useful electric range of 60 miles, the price of the range-extension hybrid might be about $6,200, 20 percent more than that of the comparable ICE vehicle. Life-cycle cost might be only 19.3 cents per mile, 11 percent less than that of the ICE despite low 1980 gasoline prices.

A "high-performance" hybrid differs from the range-extension hybrid in that it employs a larger ICE, a smaller electric motor, and a smaller battery. It is capable of all-electric operation at low speeds and accelerations, but makes the ICE instantly available when high acceleration and speed are demanded. The combined power of the ICE and the electric motor suffice for acceleration competitive with that of conventional ICE cars, and range on the ICE is unlimited. Yet the high-performance hybrid might be less expensive than either the pure electric car or the range-extension hybrid. Its drawbacks are reduced range and acceleration in all-electric operation, and increased use of gasoline in typical driving. Furthermore, the stop-start operation required of the ICE (to assist with acceleration whenever necessary in urban driving) imposes significant technical difficulties and risks exceeding those of the range-extension hybrid.

Development and construction of a high-performance hybrid was begun in 1980 for the Department of Energy by General Electric and Chrysler, the team which completed the all-electric ETV-1 in late 1979. The high-performance hybrid is designated HTV-1. In the preliminary design study preceding the HTV-1 development and construction contract, the acceleration capability of the GE/Chrysler design was estimated at 0-56 mph in 12.6 seconds, equal to that of the ICE car chosen for reference, a five-passenger 1978 Chevelle Malibu V-6 updated to 1985 conditions.[4] Price of the HTV-1 design in mass production was estimated to be 35 percent higher than that of the updated reference car, but life-cycle costs were projected to be about equal to those of the reference car. Range and acceleration of the GE HTV-1 preliminary design in all-electric operation were not reported in the summary of the design phase of the project, but would be below those of the all-electric and range-extension hybrid vehicles described in this report.[4]

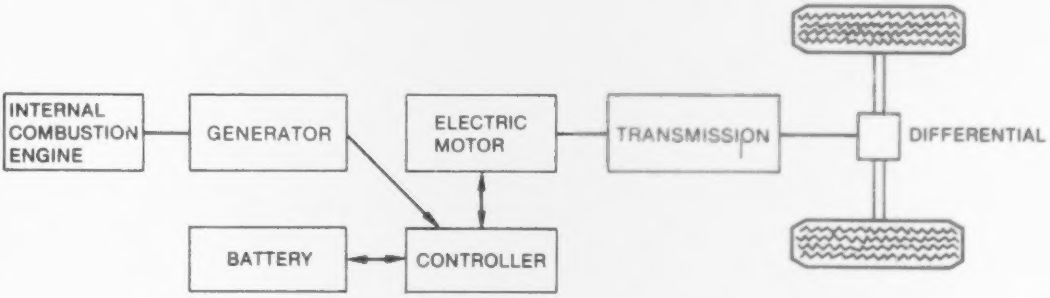
Estimated fuel use of the preliminary high-performance hybrid design is 63 percent of that which would be required by the reference car projected for 1985.[4] The range-extension hybrid, with its greater reliance on electric drive and utility power, would use around 20 percent of the fuel required by the ICE car comparable to it.

This chapter first discusses hybrid vehicles and drive trains as an extension of the electric vehicle technology presented in Chapter 3. Then it describes and compares representative examples of projected future range-extension hybrids and projected future high-performance hybrids.

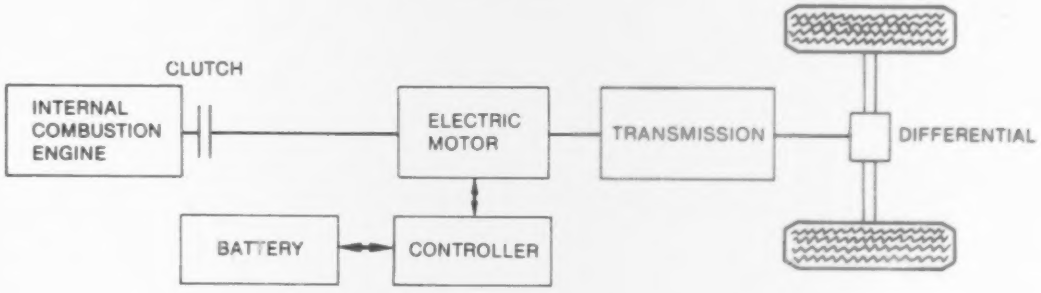
4.2 VEHICLE DESIGN

Hybrid Configurations

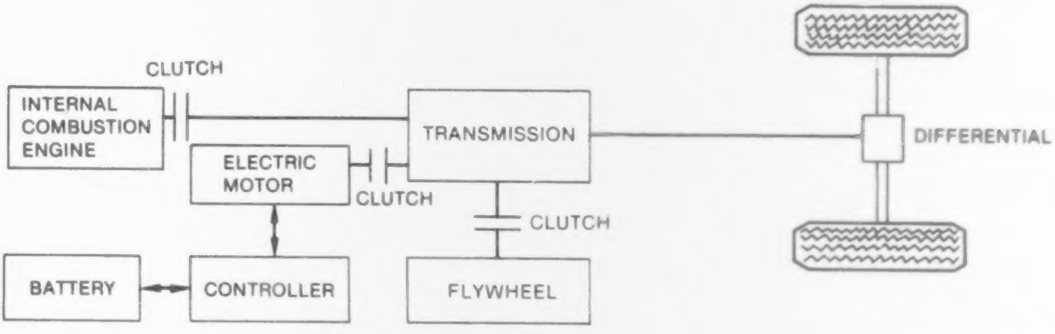
The series hybrid configuration is the most obvious of the major hybrid propulsion alternatives. It may be thought of as an electric propulsion system to which an auxiliary engine and generator are added. This is illustrated at the top of Fig. 4.1.


INTERNAL COMBUSTION ENGINE
GENERATOR
ELECTRIC MOTOR
TRANSMISSION
DIFFERENTIAL
BATTERY
CONTROLLER

SERIES HYBRID


CLUTCH
INTERNAL COMBUSTION ENGINE
ELECTRIC MOTOR
TRANSMISSION
DIFFERENTIAL
BATTERY
CONTROLLER

PARALLEL HYBRID


CLUTCH
INTERNAL COMBUSTION ENGINE
TRANSMISSION
DIFFERENTIAL
ELECTRIC MOTOR
CLUTCH
CLUTCH
BATTERY
CONTROLLER
FLYWHEEL

FLYWHEEL HYBRID

Figure 4.1 Basic Hybrid Configuration

The role played by the engine and generator in the series hybrid depends on their size. An engine-generator set with sufficient output to drive the electric motor at its maximum rated power make the battery unnecessary, and reduce the electrical equipment to performing functions ordinarily assigned to the transmission. This is the arrangement now used in diesel-railroad locomotives; it was introduced in highway vehicles as long ago as 1908.[1] With smaller engine generator sets, the battery becomes necessary to meet peak electricity demands of the propulsion motor. Very small engine generator sets lead to vehicles approaching the pure electric vehicle in capability. In any of these arrangements, recharge power for the battery may be derived either from electric utilities or the on-board generator. The larger the battery, the more use may be made of electric utilities.

The advantages of the series configuration include:

- Capability for all-electric operation.
- Regenerative braking.
- Constant-power ICE operation with high consequent ICE efficiency and low pollutant emissions.

The disadvantages include:

- The high weight and cost of an ICE and generator in addition to an electric motor large enough to meet all propulsive power requirements.
- The high losses in passing all power from the ICE through both a generator and a motor before it reaches the driven wheels.

The parallel hybrid configuration is the principal alternative to the series configuration. The parallel configuration provides direct mechanical paths between the driven wheels and both the ICE and electric motor. This eliminates the weight and cost of the generator in the series configuration, as well as electrical losses in transmitting power from the ICE to the driven wheels. In general, however, it also eliminates the possibility of operating the ICE at constant speed and load, which tends to reduce ICE efficiency and increase pollutant emissions.

The parallel hybrid may be regarded as an ICE drive train with an electric motor added to assist the ICE with maximum power demands and to provide regenerative braking. Alternatively, this same configuration may be regarded as a complete electric drive train with an ICE added to assist the electric motor and battery with both power for high acceleration and energy for long-range cruising. The configuration is illustrated at the center of Fig. 4.1. Just one version is shown; in others the locations of the electric motor and ICE may be interchanged, or the

ICE and motor may be given separate inputs to the transmission so they may run at different speeds, or the transmission may be used between the ICE and motor while the motor drives the differential directly. All these arrangements offer the essential feature of the parallel hybrid: a direct mechanical path from both ICE and motor to driven wheels.

The advantages of the parallel hybrid configuration include:

- Capability for all-electric operation.
- Regenerative braking.
- High efficiency from the ICE to the driven wheels.

The disadvantages include:

- ICE operation at varying speed and load.
- Simultaneous control of ICE and motor are generally necessary.

A flywheel hybrid is sometimes distinguished as a separate hybrid-electric configuration. It amounts to a parallel hybrid in which a flywheel is added as a short-term energy store. This is illustrated at the bottom of Fig. 4.1. A successful flywheel and associated transmission could also do much to improve either a pure electric or pure ICE drive.

The advantage of the flywheel approach is high power capability at high efficiency. With peak power demands met from a flywheel, both ICE and electric motor could be smaller in the flywheel hybrid than in the simpler parallel hybrid. Regeneration efficiency might be improved by avoiding the electrical losses in the round-trip of braking energy through the electric motor, controller, and battery. The disadvantages of the flywheel hybrid are the extra weight, cost, complexity, and technical risk associated with the flywheel subsystem.[5]

Given today's needs for increasing reliance on utility electricity rather than gasoline to propel vehicles, the parallel hybrid configuration is generally preferred. In the Phase 1 design competition of DOE's Near-Term Hybrid Vehicle Program, all four contractors chose parallel hybrid configurations.[4] Such alternatives as the flywheel hybrid (or a similar hybrid with a hydraulic accumulator) were rejected as technically uncertain or insufficiently beneficial, or both. The flywheel hybrid, in particular, provides net benefits if--and only if--the necessary flywheel and transmission can be sufficiently light, long-lived, reliable, and inexpensive. A flywheel subsystem for this sort of application is being developed for DOE's Electric Test Vehicle ETV-2,but has encountered serious setbacks in testing.[6] The ETV-2 development lags behind that of the companion ETV-1 discussed in Chapter 2.

Within the parallel hybrid configuration, there remains a wide spectrum of possible designs. At one extreme, the ICE would run continuously much as in a conventional car, with occasional help from the electric motor to provide high acceleration and possibly high speed. At the other extreme, the electric subsystem would be used alone for most travel, with occasional assistance from the internal combustion engine to meet driving demands beyond the sole capability of the electric subsystem. Most hybrid work of the late 1960s and early 1970s used the electric drive to help a small, continuously-running ICE, an arrangement which decreased the load fluctuations on the ICE and thereby improved its operating efficiencies and pollutant emissions. In the late 1970s, this approach has been replaced by the alternative in which the ICE only operates occasionally to help a basic electric propulsion system. This arrangement provides greater opportunities for supplanting gasoline use with electricity from utilities, and gives a basic electric operational capability even when gasoline is unavailable.

In hybrids wherein the ICE intermittently assists a basic electric drive, there are two alternatives distinguished by important functional and technical differences: the range-extension and the high-performance hybrid.

In a range-extension hybrid, the ICE is used only to extend the range of the vehicle beyond that provided by the battery and electric drive alone. The electric drive gives adequate acceleration for all types of driving, and adequate range for most full-day travel requirements. It alone would suffice for almost all urban driving, with all the attendent advantages of electric propulsion for reducing petroleum use and vehicular emissions of air pollutants. The ICE would be relatively small, with one-third to one-half the power output of the electric motor. It would be used mostly in highway driving, operating over a relatively narrow speed range near its maximum power. These are favorable conditions for high efficiency and low emissions. During highway cruising the ICE would provide enough extra power beyond that needed to propel the vehicle to recharge slowly the propulsion battery. This would ensure availability of electric power for occasional bursts of acceleration and higher speed or for climbing hills.

In a high performance hybrid, the ICE would be used not only to extend range beyond that of the basic electric drive, but to provide power for higher acceleration whenever the driver demanded it. Reliance on the ICE for acceleration leads to designs in which ICE output may be up to twice that of the electric motor. It also requires that the ICE operate in a stop-start mode in urban driving, contributing high power almost instantly when the driver depresses the accelerator pedal, and stopping when the pedal is released in order to conserve fuel.

Because the high-performance hybrid uses a larger ICE with larger load fluctuations for more driving conditions, it generally requires more gasoline than the range-extension hybrid. It also poses more difficult control and drivability problems because the ICE must be abruptly started and stopped and its high power output smoothly combined with that provided by the electric drive. In the range-extension hybrid, the ICE is smaller, less frequently operated, and more easily managed as a result. Its low power output could be entirely diverted, if necessary, by the electric drive to battery recharging, so that throttling of the ICE is not necessary during deceleration and stops. Starting could be manually controlled because it need not be sudden and would probably not be required at all on most travel days.

Aside from control and drivability problems, the stop-start ICE operation of the high-performance hybrid raises significant problems of engine wear and life. Two important causes of engine wear are erosion and corrosion. Erosion results from metal-to-metal contact due to inadequate lubrication. Corrosion results from chemical attack of metal surfaces by moisture and corrosive products from the combustion process. Both mechanisms are accelerated by stop-start operation, which leads to more frequent cold starts and lower average operating temperatures. During startup, especially cold startup, insufficient lubrication may be available at the pistons and piston rings, a condition exacerbated by rich fuel mixtures resulting from choking of the engine to improve cold drivability. Engines operated intermittently, with consequent low cylinder wall temperatures, tend to build up accumulations of corrosive combustion products which attack metal surfaces. Eventually, combustion products may contaminate engine oil to the point at which cold-engine sludges begin to coagulate, separate, and accumulate where oil flow is slow or restricted, further interfering with engine operation.

In short, the technical challenges posed by the high-performance hybrid exceed those of the range-extension hybrid.

Examples of Hybrid Design

Only a few hybrids have been built recently, in comparison with the much larger number of all-electric vehicles constructed. Whereas the Department of Energy has supported a number of electric vehicles for limited production and has completed the sophisticated ETV-1, it has not supported a range-extension hybrid and has only begun on a sophisticated high-performance hybrid. A recent development from industry, however, illustrates the status of the less-demanding approach, and the preliminary designs for the DOE Hybrid Test Vehicle HTV-1 reveal what may be expected from a sophisticated high-performance hybrid by the end of 1982.

The Briggs and Stratton Corporation completed a hybrid electric car in late 1979. Developed entirely on company funds, the car illustrates the potential role of the small engines manufactured by Briggs and Stratton in hybrid-electric automobiles. It is shown in Fig. 4.2.[7]

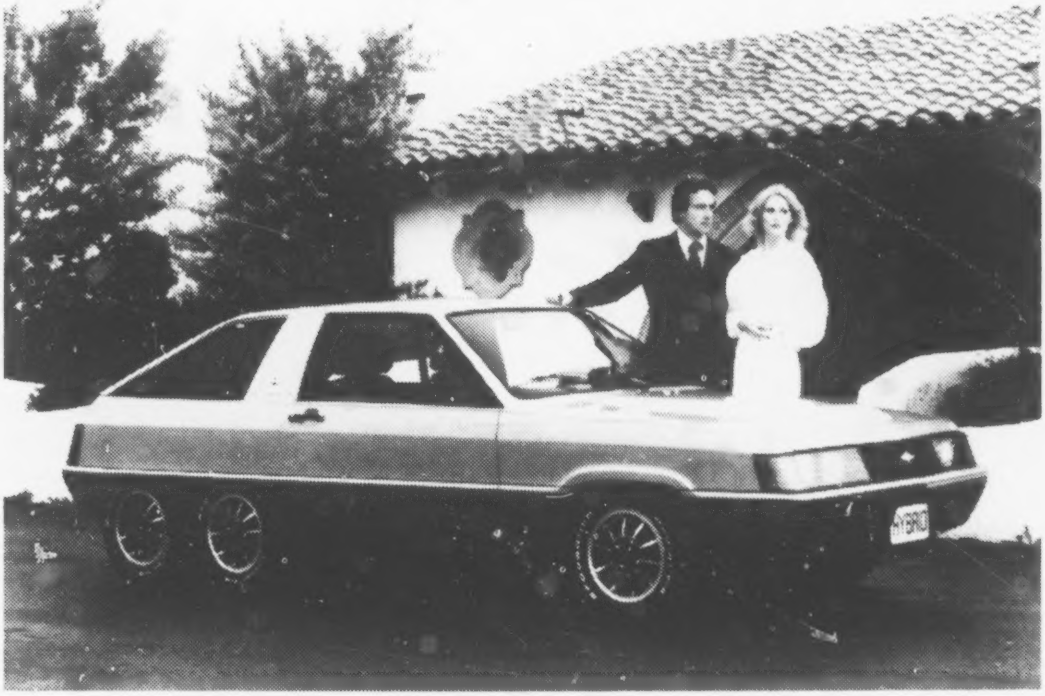


Figure 4.2 The Briggs and Stratton Hybrid-Electric Car

The Briggs and Stratton hybrid is based on a 6-wheel electric vehicle chassis from Marathon Electric Vehicle Company of Quebec (Fig. 4.3). The two extra wheels support the batteries in a "captive trailer" behind the conventional rear driving wheels. The heart of the drive train is the front mounted electric motor, which drives the rear axle through a manual clutch, 4-speed manual transmission, and differential. The free front end of the electric motor shaft can be driven by a two-cylinder gasoline engine through a one-way clutch.

The Briggs and Stratton hybrid may be operated all-electrically or with the combined power of both the motor and the ICE, at the discretion of the driver. It carries two adults, two children, and packages. Its curb weight is 3.200 pounds including a propulsion battery assembled from 12 production golf-car batteries weighing about 800 pounds which are carried in the 200-pound captive trailer. The maximum electric motor output, 20 horsepower, is reported to accelerate the car from 0 to 30 mph in 10.5 seconds and suffice for driving at speeds up to 40 mph in urban areas. All-electric range is 30 to 60 miles. The 18-horsepower

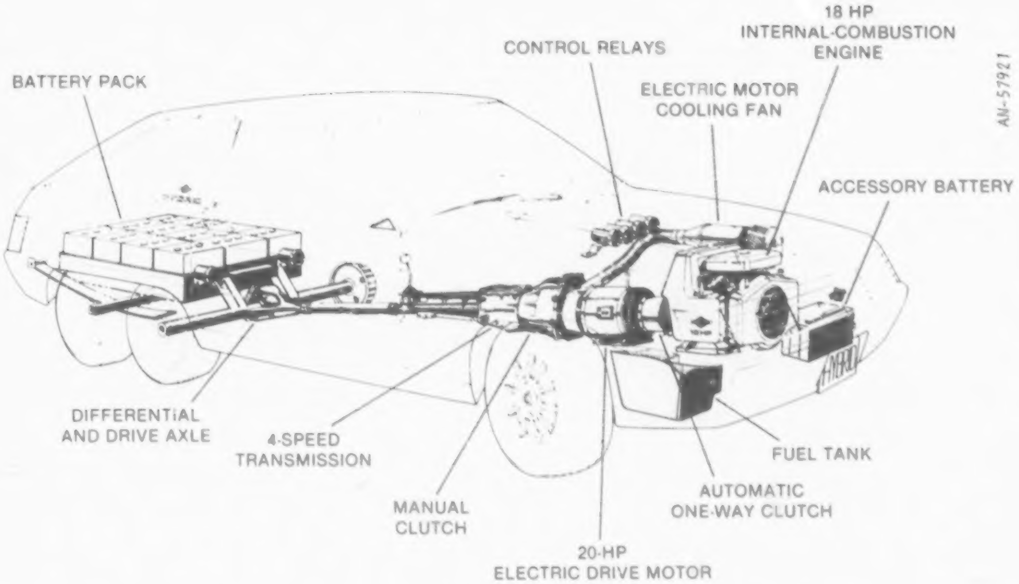

18 HP
INTERNAL-COMBUSTION
ENGINE
CONTROL RELAYS
BATTERY PACK
ELECTRIC MOTOR
COOLING FAN
AN-57921
ACCESSORY BATTERY
DIFFERENTIAL
AND DRIVE AXLE
4-SPEED
TRANSMISSION
FUEL TANK
AUTOMATIC
ONE-WAY CLUTCH
MANUAL
CLUTCH
20-HP
ELECTRIC DRIVE MOTOR

Figure 4.3 Schematic of the Briggs and Stratton Hybrid Electric Car

ICE alone gives the car unlimited cruising range at speeds up to a maximum of 45 mph. Motor and engine together allow 55-mph speed. Fuel economy on the ICE is 25-40 mpg. The controller is a simple contactor device which does not provide regeneration during braking or battery recharging from the ICE.

The Briggs and Stratton hybrid is essentially a range-extension hybrid with the low acceleration of present all-electric vehicles. With improved batteries capable of higher power output and a larger electric motor, use of the ICE could be unnecessary to reach freeway speeds. It could then be operated purely for range extension. A lower-drag body with a slightly larger engine would allow cruising at 55 mph on the ICE alone.

Other recent hybrids have been even more dependent on the ICE for assisting the electric drive in all but the least demanding urban conditions. One example is the Volkswagen Hybrid Taxi, derived from the familiar VW van by addition of an electric motor and batteries to the standard rear engine-transaxle drive train.[8] Another is the Daihatsu 1.5-ton truck developed several years ago in Japan. The major objectives of this design are quiet, emission-free operation at low speeds in crowded urban areas. The drive train configuration, shown in Fig. 4.4, is identical to that of the Briggs and Stratton hybrid except that a controller using both armature and field choppers is employed. The maximum speed of the truck on the 85-horsepower diesel ICE is about 50 mph, while on the 40-horsepower motor it is about 35 mph.[9]

The Hybrid Test Vehicle HTV-1, a high-performance design under development for the Department of Energy by a team headed by General Electric, is illustrated in Fig. 4.5. The HTV-1 is a five-passenger intermediate-size car comparable in both performance and accommodations to conventional ICE cars. The entire hybrid drive train and propulsion battery are placed in the front of the car. The car is expected to weigh about 3,950 pounds, some 800 pounds more than a comparable conventional car. Its ten lead-acid batteries will weigh 770 pounds; they will be improved state-of-the-art batteries expected from the DOE Near-Term Battery Program.[4]

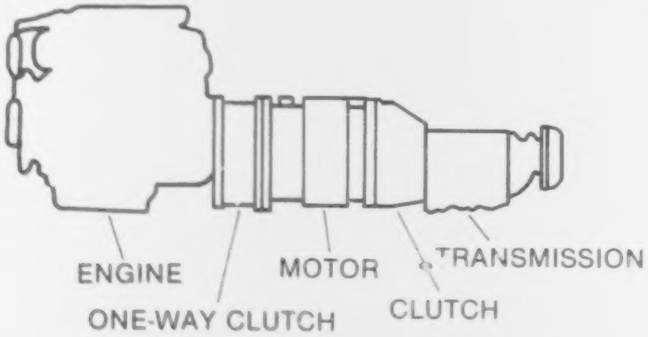

ENGINE
ONE-WAY CLUTCH
MOTOR
CLUTCH
TRANSMISSION

Figure 4.4 Power Train of Daihatsu 1.5-ton Hybrid Truck

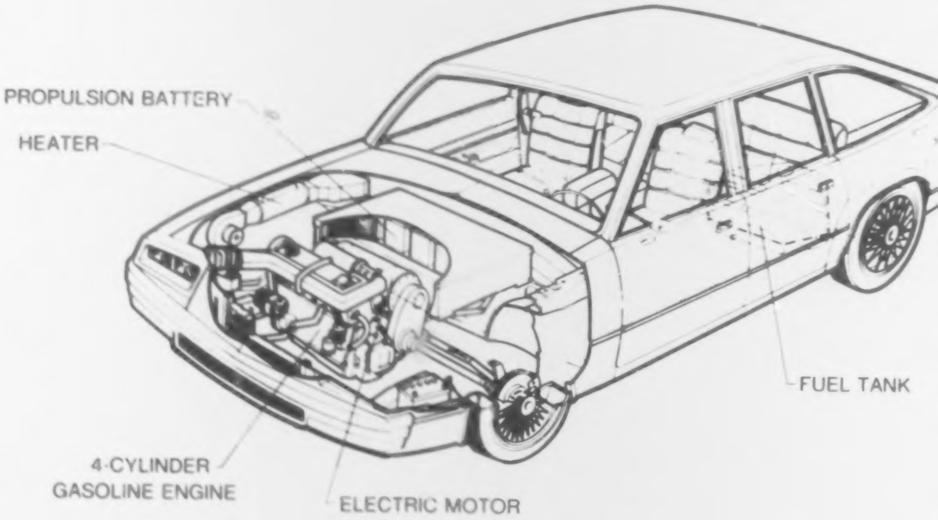

PROPULSION BATTERY
HEATER
FUEL TANK
4-CYLINDER GASOLINE ENGINE
ELECTRIC MOTOR

Figure 4.5 Schematic of DOE's Hybrid Test Vehicle HTV-1

The electric motor of the HTV-1 is a DC machine controlled by a field chopper and battery switching, with 44 horsepower peak output. It will power the "primary-electric" mode of urban driving at speeds below 31 mph. A 4-cylinder, 60-horsepower fuel-injected ICE will operate on demand for bursts of high acceleration during the primary-electric mode, and will provide the primary capability for higher-speed driving. The front wheels of the HTV-1 preliminary designs are driven by both engine and motor through a 4-speed, automatically-shifted gear box. Maximum acceleration using both engine and motor was estimated for the preliminary HTV-1 design at 0-31 mph in 5 seconds and 0-56 mph in 12.6 seconds, implying capability for accelerating from 0 to 40 mph in 7 to 8 seconds. Top speed was estimated at 93 mph.[4]

Petroleum use for the preliminary HTV-1 design was projected to be 63 percent of that for the comparable conventional vehicle.[4] More recently, General Electric has indicated that performance of the final design may be slightly reduced, an automatic 3-speed transmission substituted for the 4-speed gear box, and petroleum use decreased to 45-60 percent of that for the comparable conventional car.[10]

Design Tradeoffs

In the range-extension hybrid, increasing battery size increases range on electricity alone and thus increases the portion of total travel on electricity rather than gasoline. As in the electric vehicle, however, increasing battery size also increases vehicle weight, sticker price, energy use per mile, and life-cycle cost.

For the range-extension hybrid, then, the crucial design tradeoff is between expense and independence of the gasoline pump. The critical design parameter is range on electricity alone, as in the pure electric vehicle. The importance of long electric range is much less for the hybrid, however, because it can ordinarily continue beyond its electric range using its ICE. Short electric ranges do not limit mobility, as in the case of the electric car. Furthermore, the electric range of the hybrid can be fully utilized on all long trips, including trips too long to be undertaken by the electric car. For such trips, the owner of the electric car would have to substitute an ICE car for the entire distance.

Though available travel data are less than definitive, it appears that a range-extension hybrid with a useful electric range of 100 miles would be able to accomplish electrically about 85 percent of the distance travelled annually by the average US car. For shorter electric ranges, decreases in electrification of travel would at first be slow: with 60-mile useful range, the hybrid could still electrify about 80 percent of average annual car travel. At still shorter ranges, however, electrification would drop rapidly (see Fig. 4.6). Useful range is the distance which would be driven on electricity before starting the ICE of the hybrid. It would probably be limited to 80 percent of the maximum

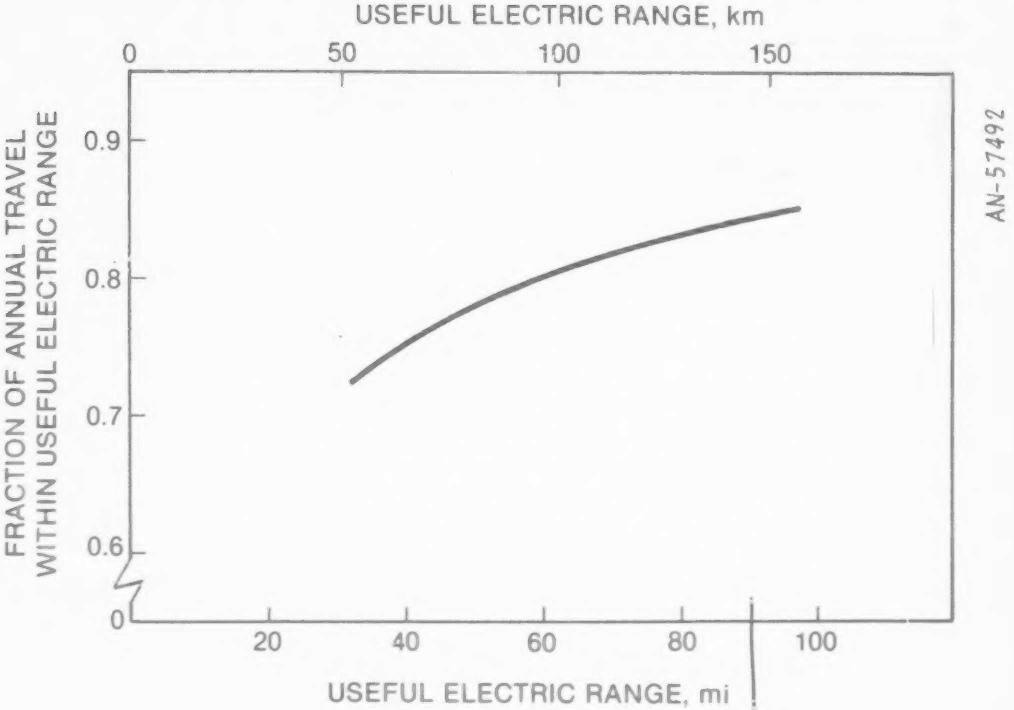


Figure 4.6 Annual Travel on Electricity Versus Useful Electric Range of Hybrid Cars

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electric range, in order to leave sufficient battery capability available for assisting the ICE with electric power for bursts of acceleration.

To project the costs which must be weighed against the benefits of increasing electrification, key characteristics for future range-extension hybrids were projected using the same methods and assumptions employed to project characteristics for pure electric vehicles (see Appendix). The projections were made for near-term hybrids with lead-acid and nickel-zinc batteries. Depending on battery size, the projected four-passenger cars with near-term batteries could offer:

- 45-105 miles useful urban range on electricity alone.
- Sticker prices of $7,000 to $10,000.
- Annual fuel usage from 70 gallons per year for the short-range cars to 50 gallons per year for the long range cars (for annual travel of 10,000 miles).

The initial and life-cycle costs of the comparable ICE vehicle are projected to be $4,470 and 21.4 cents per mile. Maximum battery weights assumed were 32 percent of vehicle test weight for lead-acid batteries, and 28 percent for nickel-zinc batteries. The minimum battery weight was 23 percent of test weight for lead-acid battery vehicles and about 19 percent for nickel-zinc vehicles. At any given range, the cars with nickel-zinc batteries are considerably lighter, about equal in sticker price, and roughly 28 percent more expensive on a life-cycle basis than the cars with lead-acid batteries due to the shorter life projected for the nickel-zinc battery.

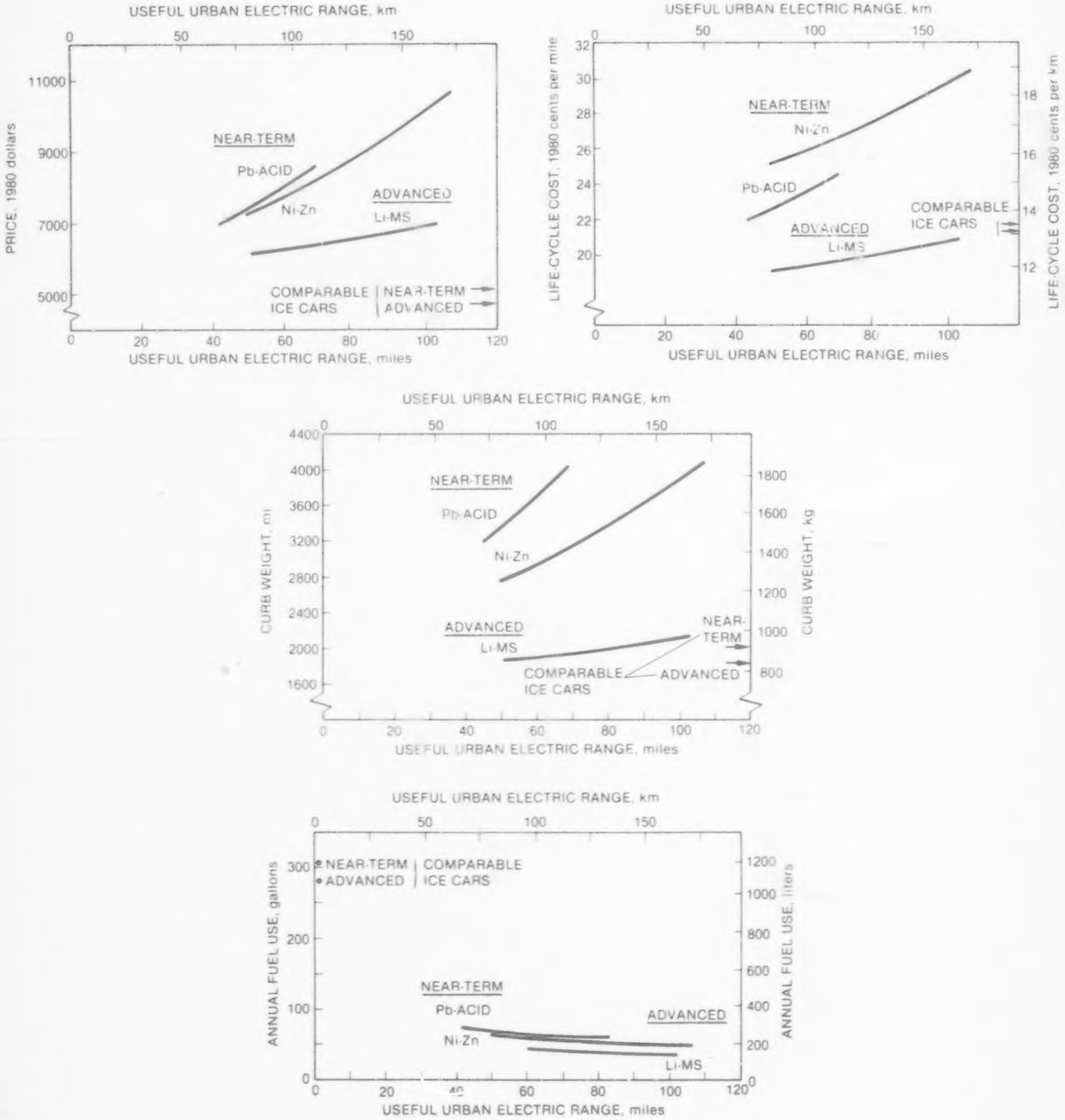
Projections were also made for four-passenger range-extension hybrids using advanced lithium-metal sulfide batteries. Depending on battery size, the projected cars would offer:

- 50 to 100 miles urban range on electricity alone.
- $6,100-7,000 sticker price.
- 19-21 cents per mile life-cycle cost.
- 45 gallons per year gasoline use at the shortest range to 35 gallons per year at the longest range (for annual travel of 10,000 miles).

The comparable conventional car would offer a sticker price of $5,140, a life-cycle cost of 21.7 cents per mile, and an annual petroleum use of 280 gallons, approximately.

Figure 4.7 further illustrates the tradeoffs between cost and petroleum use. The projections do not, however, include hybrids with the nickel-iron or zinc-chlorine batteries employed in projections for electric cars. This is because the versions of these batteries now under development have insufficient power output per pound to permit hybrid designs with relatively small batteries and short ranges. For those battery types to be used in range-extension hybrids, versions designed for higher power in relation to energy are desirable. Present design goals are better suited to pure electric vehicles, for which a lower relative level of power output is satisfactory.

A more complicated set of design tradeoffs arises for the high-performance hybrid because the designer has an additional degree of freedom: shifting acceleration power requirements from the electric motor to the internal combustion engine. In the high-performance hybrid, the ICE can be started at any time to meet acceleration requirements, even during the primary-electric operating mode. With the ICE's power instantly available, the designer is free to reduce the electric motor size and battery size at will. This makes the high-performance hybrid less expensive, but more dependent on petroleum fuel, i.e., more like an ICE car and less like an electric car.



Assumptions: Mid-1980 dollars
Useful electric range equals 80% of maximum electric range
Acceleration Capability: 0-40 mph in 10 seconds
Driving Cycle: SAE J227a, Schedule D

Source: General Research Corporation

Figure 4.7 Design Tradeoffs for Four-Passenger Range-Extension Hybrid Cars

For the near term, ICEs large enough to provide from half to two-thirds of maximum available acceleration power are favored for high-performance hybrids.[4] The design tradeoffs behind such choices were developed by four independent contractor teams during the study and preliminary design phase of the DOE near-term hybrid vehicle program. The contractors' reports detailing this work, however, are not yet generally available.

4.3 REPRESENTATIVE FUTURE HYBRID VEHICLES

Hybrid designs offering low electric range and electric acceleration capability are generally cheapest to buy and to operate over their life, at least given today's gasoline and electricity prices. By the time hybrids are marketed in high volume, however, it is likely that a spectrum of designs will be offered, including many with more than minimum electric capability. Especially if petroleum shortages and price increases recur, many buyers may prefer range-extension hybrids with long electric range and low dependence on petroleum fuels. Many others, however, may still prefer hybrids with lower prices and less electric capability or with performance as high as that of large conventional cars, despite greater petroleum use and less operational capability when it is unavailable. This section addresses both possibilities.

Range-Extension Hybrids

A maximum range of 75 miles on battery power alone is a reasonable choice for representative future range-extension hybrids. This leads to a useful electric range of 60 miles before the ICE would ordinarily be started, at 80 percent depth of battery discharge. This would be enough for electrification of about 80 percent of the annual travel by the average US automobile. This is the same level of electrification that the 100-mile all-electric car would achieve, as discussed further in Chapter 6.

Near-term four-passenger range-extension hybrids with 60-mile useful ranges and lead-acid or nickel-zinc batteries would offer:

- Sticker prices of about $8,000 or $7,800, slightly less than the prices of about $8,500 or $8,100 projected for electric cars with the same types of batteries but 69 percent or 64 percent greater than the $4,740 price of the comparable ICE car.

- Life-cycle costs of 23.5 or 26.0 cents per mile, less than the figures of 23.9 or 26.6 cents per mile estimated for all-electric versions but 5 percent or 20 percent greater than the 21.4 cents per mile for the comparable ICE car.

- Annual fuel use in average travel of about 66 or 60 gallons per year, only 22 percent or 20 percent of the 300 gallons per year projected for the comparable ICE car.

A four-passenger hybrid with advanced lithium-metal sulfide battery and 60 mile useful electric range might offer a price just 20 percent above that of the comparable ICE car, a life cost 11 percent lower, and a fuel use of only 45 gallons per year, just 16 percent of the 280 gallons per year projected for the comparable ICE car (see Table 4.1).

The range-extension hybrids weigh less and cost less than their electric counterparts because they offer less electric range and therefore require a smaller battery. The reductions in battery weight and cost exceed the weight and cost added by their ICE systems. In addition, the weight and cost of the necessary electric propulsion system and the remainder of the car are slightly reduced. For the near-term four-passenger car with nickel-zinc battery, for example, 200 pounds of expensive battery is replaced by 150 pounds of less expensive ICE system (Table 4.2).

Like pure electric vehicles, the range-extension hybrids are more expensive to buy than comparable ICE cars because of the weight and cost of their batteries and electrical equipment. On a life-cycle basis, they are more expensive due to battery depreciation and the extra costs of capital, which exceed the savings they bring on repairs and maintenance, and on energy. Further details are given in Table 4.3.

Fuel costs projected for the comparable ICE cars are about 4 cents per mile. Thus doubling the assumed gasoline price (to $2.50 per gallon) would add 4 cents per mile to the life cycle costs of the ICE cars. If gasoline prices rose from $1.25 to about $2.00 per gallon (in 1980 dollars) and other costs remained unchanged, the near-term range-extension hybrid with lead-acid battery would be no more expensive (in terms of life cycle cost) than the comparable ICE car. For the hybrid with nickel-zinc battery, the corresponding gasoline price is $2.70 per gallon. Because of the very high performance and long life projected for the lithium-metal sulfide battery, plus a low off-peak price for electricity, the advanced range-extension hybrid is already cheaper on a life-cycle basis than the comparable ICE car, even at 1980 gasoline prices.

If petroleum alone were used to generate recharge energy, the energy requirements of the lead-acid and nickel-zinc hybrids would be equivalent to those of conventional cars getting 31 to 33 mph (miles per gallon) in urban driving. The car with advanced lithium-metal sulfide batteries would increase this equivalent fuel economy to about 42 mpg. This is competitive with the projected conventional cars offering the same passenger space and acceleration, built with the same materials, and using conventional ICE drive trains, which might get 33 to 36 mpg in urban driving. If coal alone were used to generate electricity and produce synthetic gasoline, however, the near-term hybrid cars would offer the equivalent of 53 and 58 mpg, and the advanced battery car 73 mpg. This results from the inefficiencies of using coal rather than petroleum to produce gasoline. Table 4.4 summarizes these projections.

TABLE 4.1

REPRESENTATIVE FUTURE RANGE-EXTENSION HYBRID CARS

	Near-Term			Advanced	
	Pb-Acid	Ni-Zn	(ICE)	Li-MS	(ICE)
Battery Specific Energy, Wh/lb	22.7	31.8	-	68.0	-
Useful Electric Range, mi	60	60	-	60	-
Curb Weight, lbs	3750	2960	2010	1910	1810
Sticker Price, mid-1980 dollars	8020	7770	4740	6200	5140
Life-Cycle Cost, cents per mi	23.5	26.0	21.4	19.3	21.8
Electricity Use, kWh/mi	0.38	0.37	-	0.27	-
Fuel Economy, mpg	31	34	33	45	36
Annual Fuel Use, gal/yr	66	60	304	45	282

Assumptions:		
	Electricity Price	$0.03 per kWh
	Gasoline Price	$1.25 per gallon
	Hybrid Vehicle Life	12 years
	ICE Vehicle Life	10 years
	Annual Travel	10,000 mi
	ICE Use in Hybrids	20 percent
	Urban Driving Cycle	SAE J227a, Schedule D, for hybrid cars Federal Urban Driving Cycle for ICE cars
	Acceleration Capability	0-40 mph in 10 seconds
	Passenger Capacity	Four persons plus luggage

Source: General Research Corporation. Performance and cost estimates for all vehicles were made with the ELVEC and EVWAC computer models. Costs are in mid-1980 dollars and are based on mass production of all vehicles (300,000 units or more per year).

TABLE 4.2

WEIGHT AND COST BREAKDOWNS FOR REPRESENTATIVE FUTURE ELECTRIC AND RANGE-EXTENSION HYBRID CARS

	Electric		Hybrid		Change	
	Weight, lbs	Cost, $	Weight, lbs	Cost, $	Weight, lbs	Cost, $
Battery	890	2410	700	1880	-190	-530
ICE Propulsion	-	-	150	250	150	250
Electric Propulsion	340	1020	330	1000	-10	-20
Basic Vehicle	1800	4700	1780	4640	-20	-60
Total	3030	8130	2960	7770	-70	-360

Assumptions:
Near-Term Technology
Nickel-Zinc Battery
Nominal Maximum Electric Range: 100 miles - electric car
75 miles - hybrid car
Electric Propulsion Rating (Short-Term):
47 hp - electric car
46 hp - hybrid car
ICE Propulsion Rating (continuous) - 18 hp
ICE Fuel Tank Size: 7.3 gal

Source: General Research Corporation

TABLE 4.3

INITIAL AND LIFE-CYCLE COSTS OF REPRESENTATIVE FOUR-PASSENGER RANGE-EXTENSION HYBRID CARS

	Near-Term			Advanced	
	Pb-Acid	Ni-Zn	(ICE)	Li-MS	(ICE)
Initial Cost, dollars	8020	7770	4740	6200	5140
Vehicle	6410	-	4740	5300	5140
Battery	1410	-	-	900	-
Life-Cycle Cost, cents per mi	23.7	26.0	21.4	19.4	21.8
Vehicle	5.0	4.4	4.3	4.0	4.7
Battery	2.3	5.7	-	1.4	-
Repairs & Maintenance	2.0	2.0	3.9	2.0	3.9
Replacement Tires	0.6	0.5	0.4	0.4	0.4
Insurance	2.2	2.2	2.2	2.2	2.2
Garaging, Parking, Tolls, etc.	3.1	3.1	3.1	3.1	3.1
Title, License, Registration, etc.	0.7	0.6	0.5	0.5	0.5
Electricity (per electric mile)	2.2	1.9	-	1.5	-
Fuel and Oil (per ICE mile)	4.3	3.9	4.0	3.0	3.7
Cost of Capital	5.2	5.2	3.0	4.0	3.3

All costs are in mid-1980 dollars.

Assumptions:

Electricity Price	$0.03 per kWh
Gasoline Price	$1.25 per gallon
Hybrid Vehicle Life	12 years
ICE Vehicle Life	10 years
Annual Travel	10,000 miles
Travel Using ICE	20 percent
Car and Battery Salvage Value	10 percent
Cost of Capital	10 percent per year

Car and battery purchases are 100 percent financed over their useful lives.

Repair and Maintenance cost equal to that of an electric vehicle for all-electric travel, and equal to that of an ICE vehicle for travel using ICE.

Electricity cost includes a road use tax, equal to that paid by typical gasoline vehicles of equal weight via state and federal gasoline taxes.

Source: General Research Corporation. Cost categories and many entries, such as tires, insurance, garaging, etc., are based on periodic cost analyses by the Department of Transportation (see Ref. 11). All costs shown were computed by the Electric Vehicle Weight and Cost Model (EVWAC), Ref. 12.

TABLE 4.4

EQUIVALENT FUEL ECONOMIES OF FOUR-PASSENGER RANGE-EXTENSION HYBRID CARS RECHARGED FROM PETROLEUM OR COAL RESOURCES

	Equivalent Miles per Gallon[*]	
	Oil	Coal
Near-Term Cars		
Lead-Acid	31	53
Nickel-Zinc	33	58
(Comparable ICE Car)[†]	(33.0)	(33.0)
Advanced Cars		
Lithium-Metal Sulfide	42	73
(Comparable ICE Car)[†]	(35.6)	(35.6)

Assumed Conversion Efficiencies:

Crude oil to gasoline	- 89%	Coal to gasoline	- 53%
Crude oil to electricity	- 28%	Coal to electricity	- 30%

Efficiencies include losses and energy inputs in extraction of the energy resource from the ground, transportation and conversion to its final form for vehicular use, and delivery to the vehicle. Source: Ref. 13

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[*] Equivalent miles per gallon is the urban fuel economy of an ICE car requiring the same use of petroleum (for gasoline) or coal (for synthetic gasoline) as would be needed to generate recharge electricity for the hybrid car.

[†] The comparable ICE cars offer the same passenger compartments and acceleration capability as their hybrid counterparts, are built with the same materials, and use conventional ICE drive trains. Their fuel economies are projected for urban driving.

The range of the range-extension hybrid during all-electric operation would be as sensitive to head winds, grades, and other driving conditions as the ranges of all-electric cars. The importance of this sensitivity to motorists would be much less, however, because the availability of the ICE would insure against premature battery depletion before the end of a planned trip. An electric air conditioner or an electric heat pump for both cooling and heating would be attractive for the range-extension hybrid for this same reason: trip completion would not be threatened by premature battery depletion. A gasoline heater would also be facilitated by the availability of the gasoline on board for the ICE.

Comparisons between larger hybrid cars and comparable conventional cars, or between hybrid and conventional light trucks, would be like those drawn here for four-passenger cars. That is, if the sticker price of the four-passenger hybrid were 70 percent above that of the four-passenger ICE car, the sticker prices of other hybrid vehicles would also be about 70 percent above the prices of the comparable ICE vehicles.

Because of its low reliance on its ICE, the range-extension hybrid poses few technical problems beyond those of the electric vehicle on which it is based. The availability of the ICE enhances the dependability of the vehicle, since it is disconnected from the basic electric drive in most driving but can be engaged to provide propulsive power not only after battery discharge, but in the event of typical electrical system failures. Excessive ICE operation in urban areas, with attendant petroleum use and pollutant emissions, is unlikely: the driver might thus improve acceleration capability or avoid electrical recharge from utility power, but the ICE is too small to add greatly to acceleration, and operation on gasoline is considerably more expensive than on electricity. Furthermore, plugging in the car for overnight recharge at home will generally be more convenient than making stops at the filling station for gasoline.

High Performance Hybrids

Working independently, four design teams completed thorough trade-off studies and preliminary designs for high-performance hybrids for the US Department of Energy in late 1979. The four teams were headed by Fiat (the Italian auto maker), General Electric, and two small firms: Minicars and South Coast Technology, both of Santa Barbara. The trade-off studies considered typical driving needs against the performance capabilities, costs, and risks of a wide variety of future technological alternatives to choose the components and operating strategies for the preliminary designs. The General Electric study and design led to selection of the GE team for final design and construction of DOE's Hybrid Test Vehicle HTV-1, which is to be completed about the end of 1982 (see Fig. 3.5). The results of the preliminary design work have been reported by the Cal Tech Jet Propulsion Laboratory (JPL), manager of the work for the Department of Energy.[4]

The performance projected for the four preliminary designs is much like that of recent intermediate and full-size US sedans, and much higher than that of electric vehicles:

- Acceleration from 0 to 31 miles per hour in 4.3-5.0 seconds, compared with about 9 seconds for the DOE Electric Test Vehicle ETV-1 and 6-7 seconds for the range-extension hybrids and future electric cars projected elsewhere in this report.
- Acceleration from 0 to 56 miles per hour in 12.6-13.8 seconds, compared with 25-30 seconds for the ETV-1 and about 20 seconds for the range-extension hybrids and future electric cars.

The preliminary designs of the high-performance hybrids also provided cruising speeds from 55 to 80 miles per hour, maximum speeds from 80 to 110 miles per hour, and seating for either 5 or 6 passengers.

The costs of the preliminary high-performance hybrid designs exceed those of the comparable ICE cars projected by the individual study teams, but they are generally below those of range-extension hybrids and pure electric cars in this report:

- Retail prices are projected to be 20 to 60 percent above those of comparable ICE cars, whereas sticker prices of the range-extension hybrids were estimated to be 65 to 70 percent higher (with near-term batteries).
- Life-cycle costs were estimated to range from slightly less to about 25 percent above life-cycle costs for the comparable ICE cars.

Estimated fuel uses for the preliminary high-performance hybrid designs are substantially higher than those for the range-extension hybrids: 30 to 60 percent of the fuel usages projected for the comparable ICE cars, versus 20 percent for the range-extension hybrid (see Table 4.5).

Though all the preliminary designs of the high-performance hybrids employ the parallel configuration, they differ considerably in battery and drive train choices. The Fiat preliminary design places much more reliance on electric power than the others: its electric motor almost equals its ICE in power output, whereas the others use ICEs providing up to twice the power of the electric motor. The high reliance of the Fiat design on electricity is based on selection of the high-performance nickel-zinc battery. Two of the other designs employed future lead-acid batteries instead because of the higher risks foreseen in obtaining

TABLE 4.5

PROJECTED PERFORMANCE, COST, AND FUEL USE OF PRELIMINARY DESIGNS FOR HIGH-PERFORMANCE HYBRID CARS

	Fiat	GE	Minicars	SCT
PERFORMANCE				
Acceleration time, sec				
0-31 mph	5.0	5.0	5.0	4.3
0-56 mph	13.8	12.6	13.0	12.9
Speed, mph				
Cruise	75	81	55	81
Maximum	81	93	112	103
Passenger Capacity	6	5	5	6
COST (relative to ICE car[*])				
Retail price, %	121	135	140	161
Life cycle cost, %[†]	102	99	123	127
FUEL USE (relative to ICE car[*]), %	31	63	44	52

Source: JPL (Ref. 4)

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[*] The comparable 1985 ICE car for each design, as projected independently by each individual contractor.

[†] Based on prices (in 1980 dollars) of $1.38 per gallon of gasoline and 5.4 cents per kilowatt-hour of electricity.

nickel-zinc batteries with satisfactory life and overall cost. One design used nickel-iron batteries, considered intermediate in both performance and risk. Both designs not based on lead-acid batteries provided alternatives for backup use of lead-acid batteries.

Only the Fiat design, with its high electric capability, was capable of following the Federal Urban Driving Cycle without use of its ICE. This was made possible not only by the nickel-zinc battery and large electric motor, but also by assumptions of very advanced tires and low aerodynamic drag. Tire rolling resistance was assumed to be 0.45 percent, under half that assumed for other designs. The aerodynamic drag coefficient was projected to be 0.3, about 25 percent less than coefficients estimated for the other designs. The high reliance of the Fiat design on electricity led to the lowest projected annual usage of petroleum fuel, 31 percent of that for the reference ICE vehicle, whereas the other preliminary designs require up to 63 percent of the petroleum used by the reference vehicle.

Two of the designs use electric controllers which do not include expensive armature choppers. The GE design combines a field chopper with battery switching and a four-speed gear box with automatic shift, an arrangement also appropriate for near-term range-extension hybrids. The other three designs also include multispeed transmissions.

Table 4.6 offers additional details of battery and drive train characteristics for the preliminary high-performance hybrid designs. Comparison of the four preliminary designs shows clearly how projections of electric and hybrid vehicle characteristics can vary, even with clear-cut basic assumptions and groundrules, and even for periods as short as five years. The four contractors who independently produced these preliminary designs all worked towards--and met--the same minimum performance and payload requirements. All were required to utilize components and fabrication techniques within the state of the art by 1980 or earlier and amenable to mass production by the mid-1980's. They nevertheless differed to the extent of choosing nickel-zinc rather than lead-acid batteries, and projecting tires with rolling resistances differing by a factor of two. All the contractors were required to design vehicles with purchase prices competitive with those of reference ICE cars, and life costs equal to those of the reference ICE cars. None eventually projected a purchase price less than 20 percent above the projected price of the reference ICE car, but two projected life-cycle costs which were approximately equal to those of the reference ICE cars.

The high-performance hybrid approach has special advantages for application in light trucks and vans. These are basically load-carrying vehicles, and though they often serve as passenger cars with very little

TABLE 4.6

PROJECTED WEIGHT AND DRIVE TRAIN CHARACTERISTICS OF PRELIMINARY DESIGNS FOR HIGH-PERFORMANCE HYBRID CARS

	Fiat	GE	Minicars	SCT
Curb Weight, lbs	3,580	3,940	3,850	4,110
Maximum Power Ratings				
ICE, hp	50	60	65	71
Electric Motor, hp	47	44	32	40
Controller				
Battery Switching		X		
Field Chopper	X	X	X	X
Armature Chopper	X			X
Transmission Type	CVT[1,2]	4-speed gear box[3]	3-speed auto[2]	4-speed auto[2]
Battery Type	Nickel-Zinc	Lead-Acid	Lead-Acid	Nickel-Iron
Battery Fraction, percent[4]	18	18	18	13

Source: JPL (Ref. 4)

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[1] Continuously variable transmission.

[2] With lock-up torque converter.

[3] Automatically shifted.

[4] Battery weight as a percent of vehicle test weight (with 300-lb payload).

load, they are called upon to move large and heavy loads with surprising frequency even in personal rather than commercial service.[14] Electrification of heavily-loaded vehicles is unattractive because battery weight (and expense) must be increased in proportion to load weight in order to maintain range and performance. The ICE in the high-performance hybrid could much more effectively supply the extra power for adequate acceleration and range during heavily-loaded operation of light trucks and vans, yet leave unloaded and undemanding travel to the electric drive and to energy from electric utilities.

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5 INFRASTRUCTURE

5.1 INTRODUCTION AND SUMMARY

The infrastructure required for widespread use of electric and hybrid vehicles (EHVs) consists of four major parts:

- The electric utility industry, which must generate and distribute electric power for recharge.
- Facilities for convenient recharging, which may include some combination of special electric outlets at residential, commercial, and industrial parking places, service stations providing quick battery recharges or battery exchanges, and even electrified highways.
- Extractive industries and mineral resources, which must supply materials needed for batteries.
- Production, sales, and support industries, which must manufacture, merchandise, and service EHVs.

In each of these four areas, existing capabilities are impressive in relation to requirements for introducing EHVs. For example:

- In 1979 the electric utility industry generated 2.2 trillion kilowatt hours of electric energy, three times as much as necessary to electrify all 146 million cars and light trucks on US roads in 1980. In 1979 the industry operated at an average power output which was only 64 percent of its maximum output during the year, and electrifying 20 percent of all US cars and light trucks would have raised average power output to only 68 percent of maximum output during the year.
- Most residential garages and carports have standard 120-volt electric outlets capable of delivering enough energy during the eight-hour period from 11 p.m. to 7 a.m. to drive a four-passenger electric car 30 to 40 miles. Many garages have 220-volt outlets for clothes dryers capable of providing four times as much energy in 8 hours. Average daily auto use in the United States, in contrast, is only about 28 miles.
- Extractive industries are already supplying materials demands in the United States which are so great that increases due to mass production of EHVs (300,000 units per year) would only be 5 to 10 percent for near-term battery materials such as lead and nickel. Increases would be much

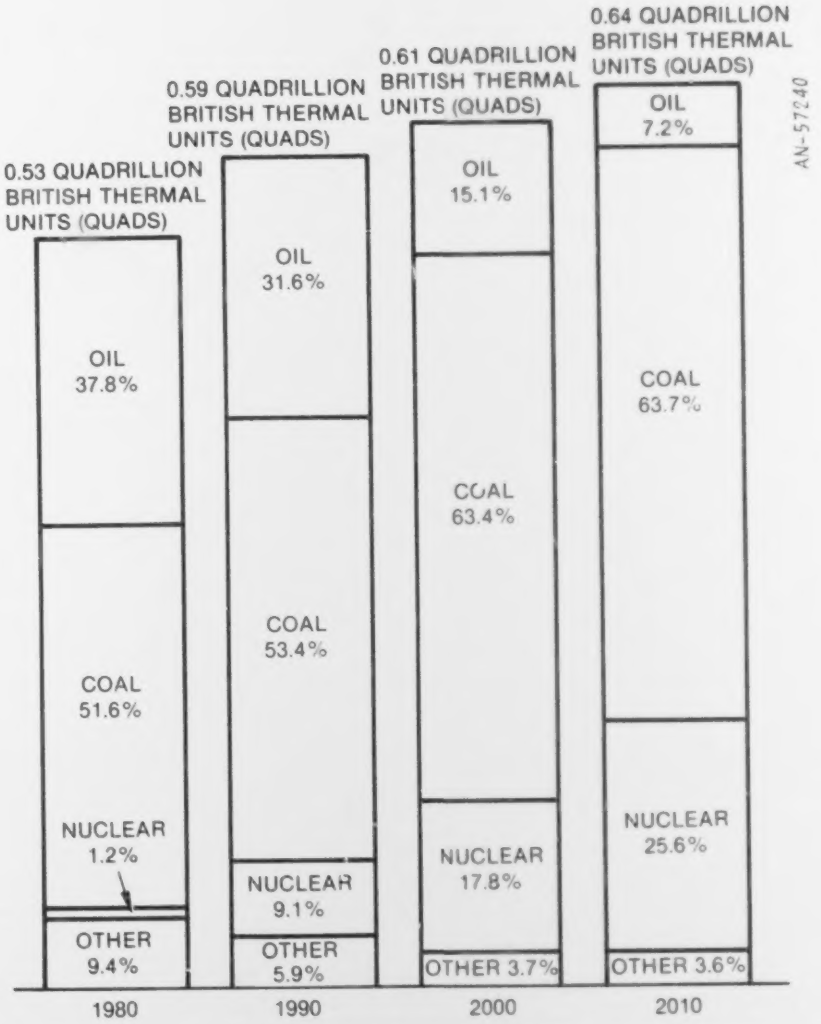
less for more widely used materials such as zinc and chlorine.

- The auto industry already produces millions of vehicles annually. They are sold and serviced through some 22,000 established dealers who already utilize factory-trained mechanics and factory-supplied parts departments.

If a major auto maker undertakes mass production of EHVs, there is little reason to assume that potential buyers will be deterred by lack of electricity or usable electric outlets, that materials suppliers will be unable to deliver sufficient battery materials, or that the auto maker itself will fail to produce, sell, and service the vehicle satisfactorily. On the other hand, there are significant changes to be made. Furthermore, widespread use of EHVs could be encouraged by appropriate changes in the infrastructure, and at the same time, national benefits from any given level of EHV use could be enhanced.

The key to realizing the potential benefits of electrification of light-duty vehicular travel is the electric utility system. Although a fifty percent increase in electricity usage of the average household would occur due to use of an EHV, the electric utility system will have sufficient capacity to handle the additional load. It is estimated that this load would range from 0.53 quadrillion BTU (quads) in 1980 to 0.64 quads in 2010, for 20 percent electrification of light-duty vehicular travel (Fig. 5.1). This represents an increase above projected electricity demand without EHVs of 6.4 percent and 2.1 percent, respectively.

The timing of the recharging load, however, is very important. Even on days of peak demand, millions of vehicles could be recharged without requiring new capacity, if most recharging is accomplished late at night when other demand is low. However, a combination of off-peak electricity pricing and selective load control will be needed to ensure that recharging occurs when the electric utility system can best handle the additional load. Considerable economic forces favor these innovations; they could simultaneously reduce prices for recharge electricity and improve utility profits. A few utilities already offer incentives for off-peak recharging, and industry attention has turned to appropriate rates and metering equipment. Still, it is unclear whether most will have adopted the practice before large-scale introduction of EHVs. It is clear, however, that the widespread use of EHVs is feasible if good use is made of the existing and planned electric utility system. If, on the other hand, much recharging makes use of on-peak or near-peak electricity, the new generating plants will have to be built to accommodate the additional demand. This could present an obstacle to the market penetration of EHVs because of the existing public resistance to the development of new power plants, particularly those employing nuclear fuels. It would also increase costs of producing recharge electricity.



Source: Recharge Capacity Projection System (RECAPS) General Research Corporation

Assumptions: The RECAPS model schedules the use of nuclear, coal, and hydroelectric facilities before oil and gas facilities, and base-load facilities before intermediate and peaking facilities to minimize operating costs. Recharging is controlled to maximize the use of off-peak power available during late night and early morning hours when demand is lowest. The model makes use of capacity and demand projections developed by the electric utility companies in 1979. Energy required was assumed to be 0.5 kilowatt-hours per mile at the charging outlet. This value reflects a mix of cars and light-duty trucks to electrify 20 percent of light-duty vehicular travel in 1980, 1990, 2000, and 2010 (Table 6.1). Vehicles were assumed to be distributed uniformly across the United States based on population. They were also assumed to travel an average of 10,000 miles per year. Electrical distribution system efficiency was assumed to be 90 percent.

Figure 5.1 Electric Energy Required Annually to Electrify 20 Percent of Light-Duty Vehicular Travel, by Type of Fuel Used

The electric utility industry is currently in the process of shifting away from the use of petroleum to other sources of energy. One of the major objectives of the use of EHVs is to further reduce national consumption of petroleum and dependence on foreign oil. Except in a few regions, most energy needed to recharge EHVs would be derived from nonpetroleum fuels, primarily coal and nuclear. For 20-percent electrification of light-duty vehicular travel, more than 50 percent of recharging energy would be derived from these sources in 1980, and by 2010 they would account for nearly 90 percent (Fig. 5.1). During this period, the use of petroleum to generate recharge energy would continue to decline.

Most cars used in the United States are parked at family residences at night, where it would be easiest and cheapest to provide high-power electric outlets for recharging. The number of EHVs that could be recharged at residences is limited primarily by the availability of off-street parking. Statistics indicate that about 60 percent of all cars in metropolitan areas (40 percent of all cars) are located at single-family residences with off-street parking.[1] Another 25 percent are located at multi-family dwellings with off-street parking.

Recharging away from home could be accomplished by a system of coin-operated outlets at parking lots, quick-charge service stations, battery exchange stations, and electrified highways. Although the ability to recharge away from home would help remove the range limitations of electric vehicles, the associated costs, which must eventually be borne by the consumer, would be high and will probably limit the extent of ultimate implementation. The fact that in some instances on-peak or near-peak electricity would have to be used for such recharging compounds the problem.

The demand for large quantities of steel, iron, rubber, zinc, copper, and aluminum used in the manufacture of automobiles will be little affected if EHVs replace conventional cars. This is primarily because EHVs will require the same types of structural components as existing vehicles. Although the drivetrain will change considerably, the materials used to manufacture it will be similar to those used in conventional cars. The biggest change will be in the primary demand for those materials used in the manufacture of propulsion batteries. Increases in US demand due to 20-percent electrification of US light-duty vehicles would fall in the 10-75 percent range by 2010. Corresponding increases in world demand would fall in the 5-35 percent range. Although identified resources of all battery materials in the United States, except aluminum, cobalt, lithium, and nickel, would be adequate to electrify much more than 20 percent of light-duty vehicular travel in the 1985-2010 time period, insufficient quantities are economically extractable. However, there are more resources not yet discovered, and it is probable that increased demand could provide the incentives necessary for enlarging the production facilities and increasing exploration for new resources.[2]

World resources of all materials considered appear to be sufficient to electrify much more than 20 percent of light-duty vehicular travel in the US, as well as supply the projected demand from other users. This additional demand would necessitate significant expansion of capacity, however, and worldwide adoption of EHVs at the same level as in the United States would multiply resource and production requirements by 3-4 times.

Most manufacturing plants, materials, and operations will be little changed by the introduction of EHVs. The functions of those people who distribute, lease, and sell vehicles will also remain virtually unchanged. Those industries that would be affected are the electrical and electronic component manufacturers who produce motors, controllers, and chargers, as well as the battery manufacturing industry. Growth in employment, production, distribution, and market share is expected for each of these industries.

With at-home recharging and the high reliability of electric drive, fewer garages and service stations will be necessary. Service personnel will require some training in maintenance of electrical components, but most service will be for familiar components such as steering, brakes, suspension, and the like. In addition, electric motors, controllers, chargers, and battery-related parts are more reliable than corresponding components of an internal combustion engine system. This, coupled with the extensive capabilities of the major manufacturers to produce and maintain new technology vehicles, should help to minimize problems associated with support.

5.2 THE UTILITY SYSTEM

Recharging EHV propulsion batteries will require the use of the electric utility system, private distribution systems, and EHV recharge systems (Fig. 5.2). The purpose of the electric utility system is to deliver electric power to the consumer. This system consists of power plants to generate electricity, high-voltage transmission lines that carry the electricity from the power plants to urban areas, substations which prepare the electricity for use by consumers, and a distribution system which delivers the electricity to specific residential, commercial, and industrial users.

Since most recharging of EHVs is likely to be concentrated in residential areas, it might be necessary to expand the capacity of the residential distribution system if extremely large numbers of EHVs are utilized. Primarily this would entail increasing transformer capacities to accommodate additional household demand. Although a detailed analysis of electric utility distribution system requirements, potential problems, and costs has not been performed, it is expected that the existing system could accommodate 20 percent electrification of light-duty vehicular travel through 2010.

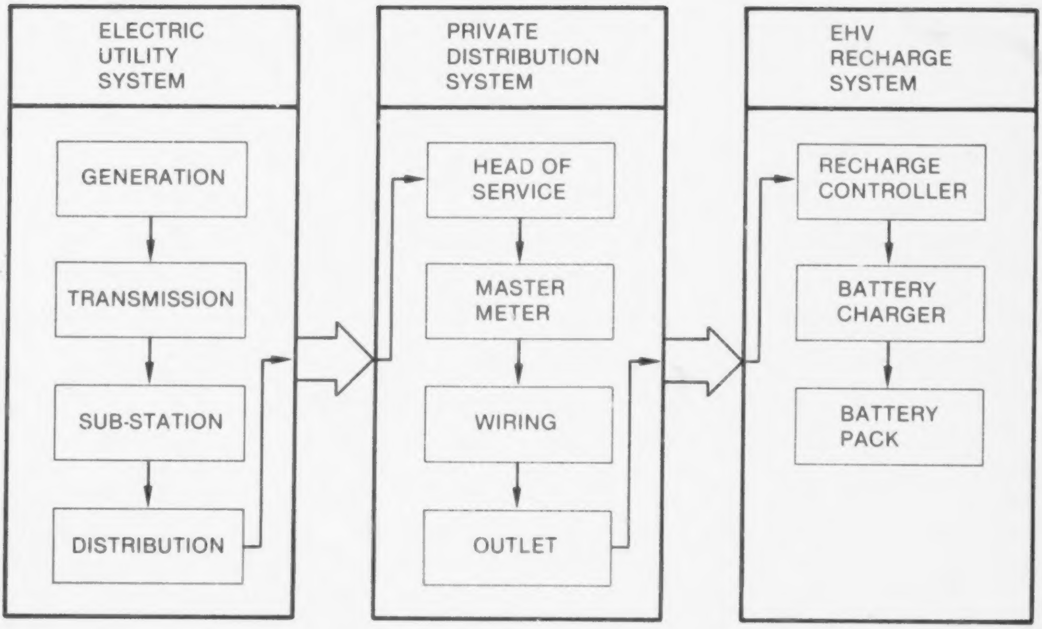

ELECTRIC UTILITY SYSTEM
GENERATION
TRANSMISSION
SUB-STATION
DISTRIBUTION
PRIVATE DISTRIBUTION SYSTEM
HEAD OF SERVICE
MASTER METER
WIRING
OUTLET
EHV RECHARGE SYSTEM
RECHARGE CONTROLLER
BATTERY CHARGER
BATTERY PACK

Figure 5.2 Electric and Hybrid Vehicle Recharging Infrastructure

The purpose of the private distribution system is to receive and distribute electricity on the consumer's property. This system connects to the electric utility system at a transformer located near the consumer's property. The connection is made with the head of service, which essentially is a junction box. The remainder of the system consists of a device which meters electricity usage, wiring which distributes the electricity within the user's residence or business, and--in the case of EHVs--an electric outlet used to supply the vehicle with recharge energy.

The purpose of the EHV recharge system is to store electrical energy in the vehicle's propulsion batteries. This system consists of a device to control and time the recharging process, a battery charger to convert alternating current to direct current at the proper voltage, and a battery pack which stores the energy. The charge controller and charger may be physically located on or off the EHV itself.

A variety of controller techniques and hardware are currently available for use in this application. Although a complete technical discussion of what is available is beyond the scope of this report, it is important to understand the two major functions of this type of device. First, it should interrupt service on command from the utility, so that overloading of the electrical system during occasional hours of very high demand can be avoided. This selective load control has long been used in various regions within the United States for industrial users and for residential water heating appliances. Second, it should provide separate metering for off-peak electricity consumption, which can then be encouraged with a special off-peak rate. This reduced rate can profitably be offered by electric utility companies during hours of low demand because most power is then provided by existing base load units using inexpensive fuels.

In the most advantageous situation, the electric utility works with both interruptible loads and off-peak pricing. In this case, the utility installs in each participating household both an off-peak meter and a remote controller for electric water heaters, air conditioners, or other large loads such as EHV battery chargers. Then the utility can interrupt lower-priority service if peak prices are insufficient to keep demand within available capacity. This may happen if higher late-afternoon prices alone prove insufficient to occasionally discourage the operation of air conditioners, for example, on extremely hot summer days when demand is high.

In order to induce customers to accept remote controllers and the associated possible inconveniences, utility companies generally offer reduced rates as an incentive. In addition, since the utility gains the added benefits of load leveling and possible higher utilization rates, they often provide the required hardware at no additional cost to the consumer.

Interruptible, off-peak recharging of EHVs constitutes a new load which would utilize existing equipment and lower-cost fuels more intensively. Resultant costs per kilowatt-hour would be low so that the utility could offer bargain rates for recharging and at the same time increase its profits. Thus both the utility and the consumer could benefit substantially from interruptible and off-peak recharging. Accordingly, the utility impacts presented here assume that EHVs are recharged during late night and early morning hours at reduced off-peak rates, under control of a utility-operated remote device. There has been little study of on-peak recharging, but it would clearly increase costs, increase petroleum use, and reduce sharply the number of EHVs which could be accommodated without additional generating plants. At the peak hour, relatively little coal-fired or nuclear capacity is ordinarily idle, so much more generation of recharge electricity would require use of petroleum-fueled facilities than very late at night.

The use of EHVs would increase the average household's electricity usage roughly 50 percent. Overnight recharging would require 13.2 kilowatt-hours per vehicle for an average driving day. This is nearly 20 percent greater than the daily requirement for a residential water heater, the biggest energy user among typical household appliances (Table 5.1). Even with reduced rates for interruptible and off-peak recharging, an EHV would be a major factor in total household electricity costs, probably adding about 25 percent to the total bill.

TABLE 5.1

USE OF ELECTRIC ENERGY IN HOUSEHOLDS

	Annual Energy Use, kWh[1]	Annual Energy Cost, $1980[2]	Average Daily Energy Use, kWh
Electric or Hybrid Car	4,828	145	13.2
Water Heater	4,040	242	11.1
Kitchen Range and Oven	3,061	184	8.4
Room Air Conditioner	2,387	143	6.5
Lighting	1,870	112	5.1
Freezer	1,534	92	4.2
Refrigerator-Freezer	1,268	76	3.5

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[1] Assumes approximately 0.5 kWh per mile is required for a near-term, four-passenger, subcompact electric car driven 27.4 miles per day (10,000 miles per year). Estimates for the other appliances were taken from a report entitled "Energy Efficiency Program for Appliances," Midwest Research Institute, Kansas City, MO, February 1977.

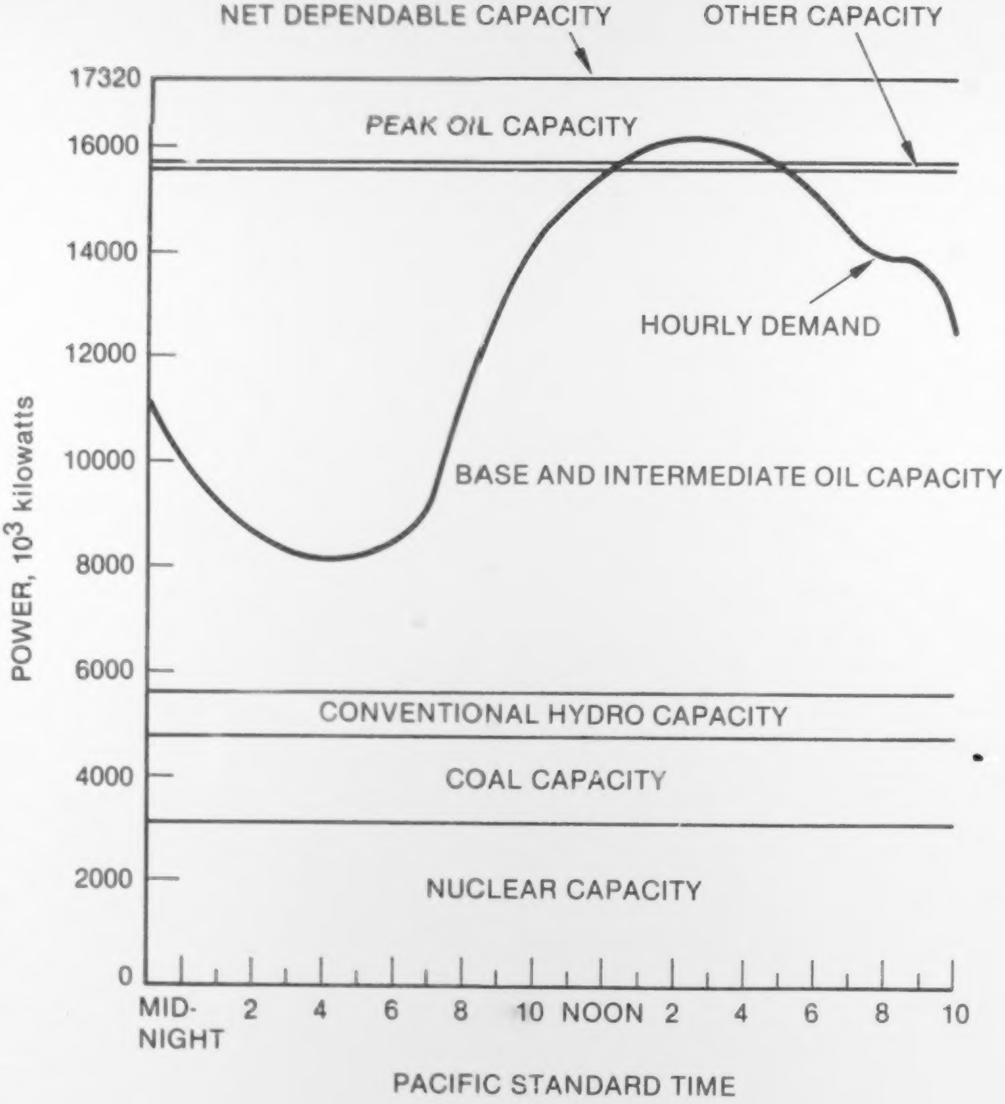
[2] Assumes that the price of electricity used for electric and hybrid vehicles is 3 cents per kWh to encourage off-peak recharging. The price assumed for the other appliances is 6 cents per kWh, even though they may also make some use of off-peak energy.

The utilities will be able to handle the additional load generated by EHVs because the pattern of demand typically fluctuates such that nearly half of a utility's potential capacity is unused much of the time. Even on those days when demand is the greatest, sufficient capacity is available to electrify as much as 50 percent of light-duty vehicular travel (given off-peak recharging) without requiring any additional capacity beyond that now planned. With greater improvements in power sharing between utilities, this percentage could be even larger. For example, analysis of the projected hourly demand on the peak summer day of 1985 for Southern California Edison shows that the load during the late night and early morning is very much less, leaving idle almost half the capacity required to meet the peak hourly demand of the day (Fig. 5.3). Even after allowance for maintenance and repair, much of this idle capacity could reasonably be put to use for recharging EHVs.

In most parts of the United States, the hours of maximum demand come in the late afternoon on hot summer days. During the winter there is a secondary late-afternoon maximum resulting from extensive use of electric heating and lighting on cold, dark winter days. Annual minimum demand is typically recorded during the spring or fall, and ordinarily on weekends when commercial and industrial activity is least. During this time, as is the case during most of the year, there is a large idle capacity available throughout all hours of the day. As a result, it would be possible to accommodate recharging of EHVs even during peak hours on many days.

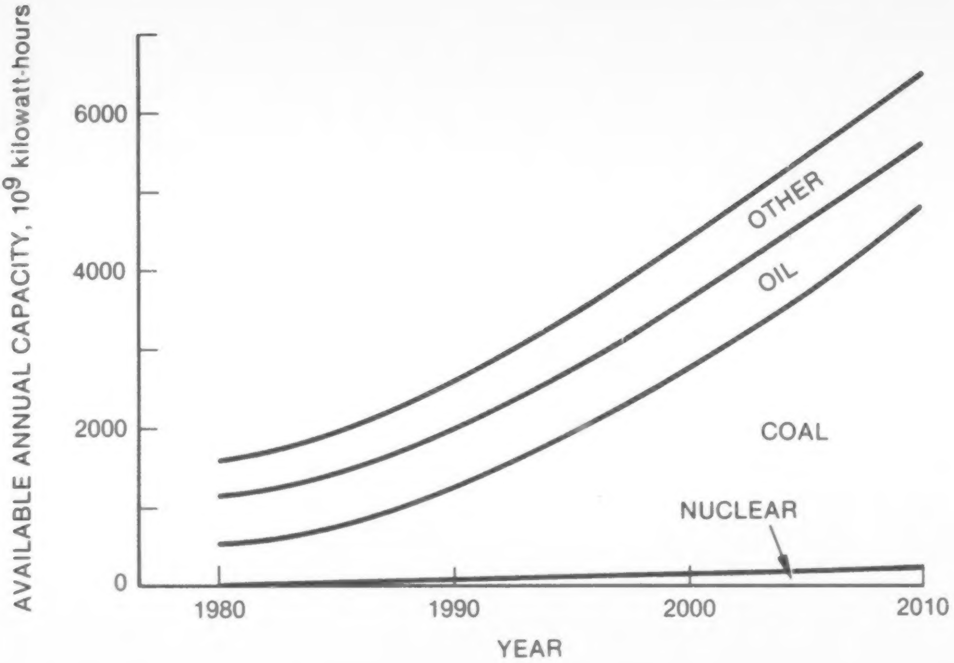
Total "available annual capacity" is defined as the difference between the electricity that can be generated using all of the normally-available generating units in the United States, adjusted to reflect maintenance and equipment failure, and the country's annual total demand for electricity. Projections of available annual capacity for 1980-2010 are shown in Fig. 5.4. The availability of coal as a major fuel for use in generating recharge energy is projected to undergo rapid growth during the next 30 years. By the year 2010, nearly 70 percent of all available capacity could be generated by coal, whereas oil and nuclear power would account for only 12 and 3 percent, respectively. However, the specific fuel mix of available capacity varies greatly from company to company and region to region. In the year 2000, it is projected that the Northeast, Mid-Atlantic, and West regions will have significant capacity available from oil; the East-Central, Mid-America, and Mid-Continent regions will have even more significant coal capacity available; and the Northeast, Mid-Continent, and West regions will have the most nuclear capacity available (Fig. 5.5). The dominance of the "other" fuel category in the Texas region is primarily due to the extensive use of gas.

If electric vehicles require less than total available capacity for recharge, utilities which have both oil-fired and other available capacity will avoid the use of oil wherever possible. Accordingly, for



Source: Recharge Capacity Projection System (RECAPS), General Research Corporation

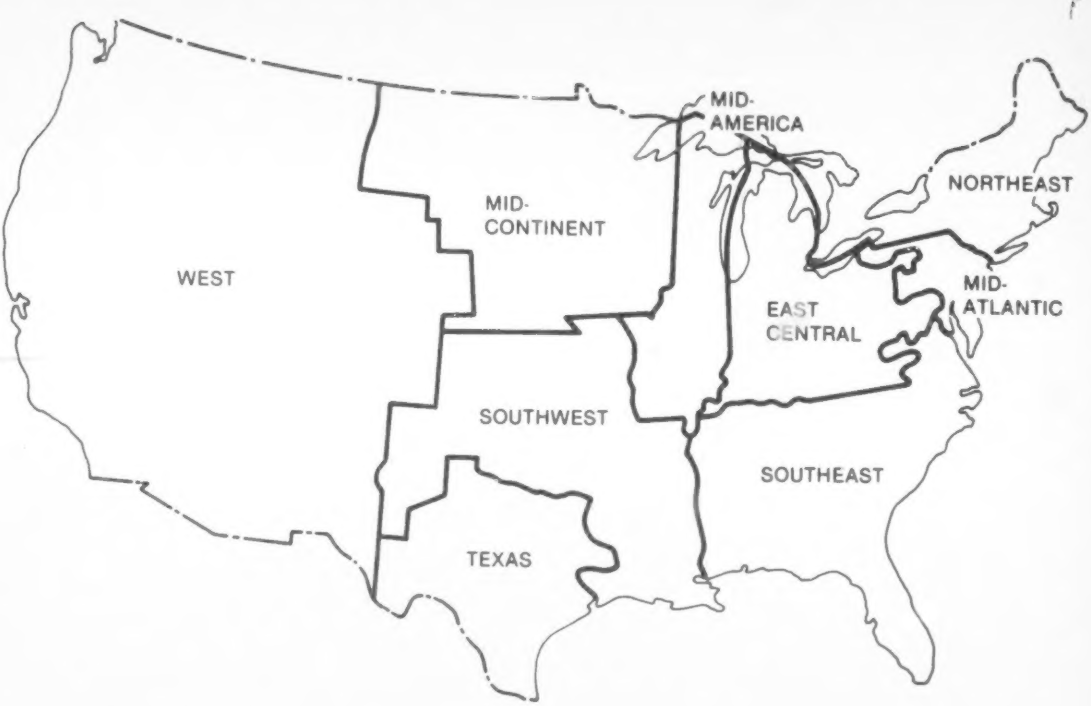
Figure 5.3 Hourly Demand and Net Dependable Capacity for a Single Utility (Southern California Edison Company, projected peak summer day, 1985)



Source: Recharge Capacity Projection System (RECAPS), General Research Corporation

Assumptions: The RECAPS model schedules the use of nuclear, coal, and hydroelectric facilities before oil and gas facilities, and base-load facilities before intermediate and peaking facilities to minimize operating costs. The model makes use of capacity and demand projections developed by the electric utility companies in 1979.

Figure 5.4 Annual Capacity Available for Generating Recharge Electricity


MID-AMERICA
NORTHEAST
MID-CONTINENT
WEST
EAST CENTRAL
MID-ATLANTIC
SOUTHWEST
SOUTHEAST
TEXAS

REGION	REGIONAL CAPACITY, 10^9 kWh	PERCENT OF REGIONAL CAPACITY			
		NUCLEAR	COAL	OIL	OTHER
NORTHEAST	225.0	13.5	4.0	59.7	22.8
MID-ATLANTIC	262.9	0.1	31.5	50.6	17.8
EAST CENTRAL	799.1	1.4	83.8	8.2	6.6
SOUTHEAST	992.0	1.2	64.4	20.4	14.0
MID-AMERICA	392.7	1.1	81.0	16.8	1.0
SOUTHWEST	580.0	1.3	58.9	16.1	23.7
MID-CONTINENT	172.8	9.4	76.2	14.2	0.2
TEXAS	331.4	0.1	32.7	8.5	58.7
WEST	637.5	8.0	45.0	27.7	19.3

Source: Recharge Capacity Projection System (RECAPS), General Research Corporation

Assumptions: The RECAPS model schedules the use of nuclear, coal, and hydroelectric facilities before oil and gas facilities, and base-load facilities before intermediate and peaking facilities to minimize operating costs. The model makes use of capacity and demand projections developed by the electric utility companies in 1979.

Figure 5.5 Regional Fuel Mix of Annual Capacity Available for Generating Recharge Energy in 2000

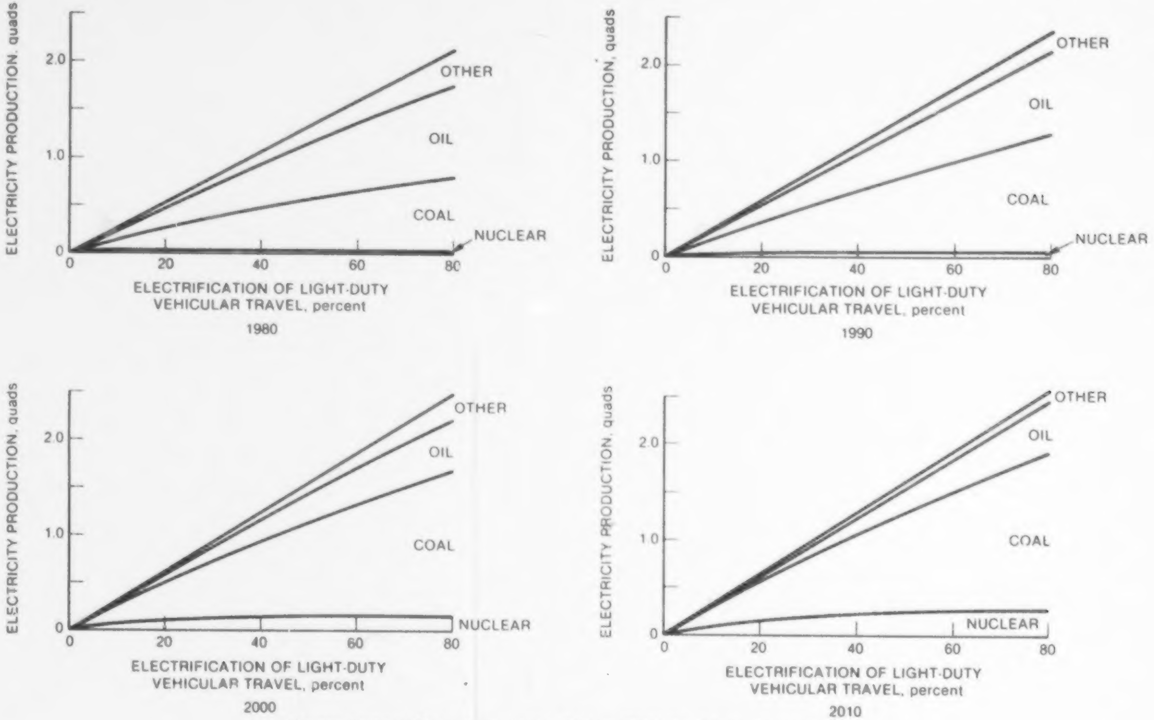
low levels of electric vehicle use coal would become much more important in relation to oil for recharging (see Fig. 5.6).

As with total available capacity, the mix of fuels required to recharge EHVs at any given level of usage would differ greatly from region to region. Because of this variation, it will be important to explore the possibility of encouraging EHV use first in those cities where it would provide the greatest reduction in petroleum usage. Thus far, these regional-type issues and their associated impacts, institutional barriers, policy implications, etc. have not been studied in detail. However, an analysis of the regional fuel mix impacts for one-percent electrification of light-duty vehicular travel was performed to determine where initial EHV implementation could best be directed (Table 5.2). At this level of market penetration, the best areas for EHV use in terms of saving petroleum would be the Mid-Atlantic, the East-Central, and the Mid-Continent regions. The least attractive would be the Northeast and West Regions. Some of these regions are so large and diverse, however, that individual cities within them are much more attractive for EHV use than the entire region. Denver in the West region is a good example; it is far less reliant on petroleum-fired capacity than the other major cities in the region (San Diego, Los Angeles, San Francisco, and Seattle).

At the one-percent level of travel electrification, the Mid-Atlantic, East-Central, and Texas regions would make heavy use of coal, and the Mid-Continent region would make heavy use of nuclear power. Since this level of EHV use would require only a relatively small portion of the total annual unused capacity available, the regional fuel mix would vary greatly. For example, although the Mid-Atlantic is dominated by oil in terms of total available capacity, very little would be used for one-percent electrification of light-duty vehicular travel. Instead, unused coal capacity would be sufficient to provide the necessary energy.

Although regional impacts on all fuels have not been analyzed for 20-percent electrification of light-duty vehicular travel, an analysis has been made which considered the national impact on petroleum usage over the entire range of possible market penetrations (Fig. 5.7). With the passage of time, less and less petroleum would be needed to recharge EHVs because of the efforts of industry to shift to coal and nuclear facilities. On the other hand, as more EHVs are used in any given year, an increasing percentage of the recharge energy would come from petroleum. For example, in 2010 petroleum usage in generating recharge electricity would increase from 8 percent up to 20 percent as electrification of light-duty vehicular travel increased from 20 percent to 80 percent.

The utilization of EHVs would shift consumption of oil from automobiles to the electric utility industry. However, it would do so at a



Source: Recharge Capacity Projection System (RECAPS), General Research Corporation

Assumptions: The RECAPS model schedules the use of nuclear, coal, and hydroelectric facilities before oil and gas facilities, and base-load facilities before intermediate and peaking facilities to minimize operating costs. Recharging is controlled to maximize the use of off-peak power available during late night and early morning hours when demand is lowest. The model makes use of capacity and demand projections developed by the electric utility companies in 1979. Energy required was assumed to be 0.5 kilowatt-hours per mile at the charging outlet. This value reflects a mix of cars and light-duty trucks to electrify 1 to 80 percent of light-duty vehicular travel in 1980, 1990, 2000, and 2010 (Fig. 5.2.1). Vehicles were assumed to be distributed uniformly across the United States based on population. They were also assumed to travel an average of 10,000 miles per year. Electric distribution system efficiency was assumed to be 90 percent.

Figure 5.6 Projected Use of Fuels for Recharging Electric and Hybrid Vehicles

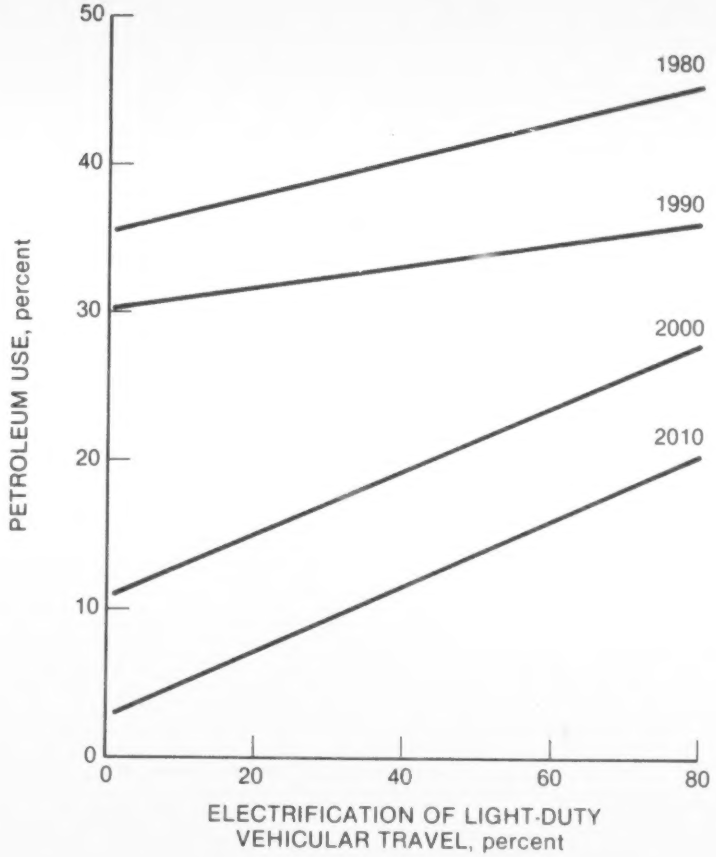
TABLE 5.2

REGIONAL FUEL MIX FOR ONE-PERCENT ELECTRIFICATION OF LIGHT-DUTY VEHICULAR TRAVEL IN 2000

	Fuel Mix, percent			
Region	Nuclear	Coal	Oil	Other
Northeast	33.8	22.0	36.7	7.5
Mid-Atlantic	2.8	97.2	0.0	0.0
East-Central	14.4	85.2	0.0	0.4
Southeast	35.3	64.2	0.5	0.0
Mid-America	43.1	56.0	0.6	0.3
Southwest	11.6	71.3	7.4	9.7
Mid-Continent	66.3	31.7	0.0	2.0
Texas	0.3	86.6	9.6	3.5
West	8.9	60.7	21.5	8.9
National Totals	21.6	64.0	10.1	4.3

Source: Recharge Capacity Projection System (RECAPS), General Research Corporation.

Assumptions: The RECAPS model schedules the use of nuclear, coal, and hydroelectric facilities before oil and gas facilities, and base-load facilities before intermediate and peaking facilities, to minimize operating costs. Recharging is controlled to maximize the use of off-peak power available during late night and early morning hours when demand is lowest. The model makes use of capacity and demand projections developed by the electric utility companies in 1979. Energy required was assumed to be 0.5 kilowatt-hours per mile at the charging outlet. This value reflects a mix of cars and light-duty trucks to electrify one percent of light-duty vehicular travel in 1980, 1990, 2000, and 2010 (Table 6.1). Vehicles were assumed to be distributed uniformly across the United States based on population. They were also assumed to travel an average of 10,000 miles per year. Electrical distribution system efficiency was assumed to be 90 percent.



Source: Recharge Capacity Projection System (RECAPS), General Research Corporation

Assumptions: The RECAPS model schedules the use of nuclear, coal, and hydroelectric facilities before oil and gas facilities, and base-load facilities before intermediate and peaking facilities to minimize operating costs. Recharging is controlled to maximize the use of off-peak power available during late night and early morning hours when demand is lowest. The model makes use of capacity and demand projections developed by the electric utility companies in 1979. Energy required was assumed to be 0.5 kilowatt-hours per mile at the charging outlet. This value reflects a mix of cars and light-duty trucks to electrify 1 to 80 percent of light-duty vehicular travel in 1980, 1990, 2000, and 2010 (Fig. 5.2.1). Vehicles were assumed to be distributed uniformly across the United States based on population. They were also assumed to travel an average of 10,000 miles per year. Electric distribution system efficiency was assumed to be 90 percent.

Figure 5.7 Percent of Recharge Energy Demand from Petroleum

greatly reduced rate because much of the energy would be derived from coal and nuclear power plants. Even though this would result in a net national reduction in oil consumption, it would increase the use of petroleum by the electric utility industry. This is because increases in demand tend to require the operation of some peaking and intermediate units, rather than base generating units, and these generally are less efficient and require the use of petroleum. In February of 1980, the mix of fuels used by the electric utility industry to satisfy national demand was 10 percent nuclear, 52 percent coal, 23 percent oil, and 25 percent from other sources.[3] These figures not only represent an effort to convert generating units from oil use to alternative fuels, but also reflect changes in fuel selection policy which establish oil as one of the least cost-effective fuels. In comparison, the projected mix required to generate energy needed to electrify 20 percent of light-duty vehicular travel in 1980 would be 1 percent nuclear, 52 percent coal, 38 percent oil, and 9 percent from other sources.

5.3 CHARGING PROVISIONS

5.3.1 Chargers

Electric and hybrid vehicles require a charger to interface between the electrical outlet and the batteries during recharging. The charger converts ordinary alternating current (AC) to the direct current (DC) necessary for battery charging, delivering it at the proper voltage for the type of battery being recharged, its state of charge, and the overall rate of recharge. Little attention has been given in the past to developing superior chargers for on-road electric vehicles, but the engineering design problems should not pose any insurmountable obstacles. Development goals are to produce chargers which:

- Maximize battery life by controlling amount and rate of recharge.

- Have high efficiencies. Present chargers deliver 60 to 70 percent of input electricity to the batteries; these efficiencies should be raised to 90-95 percent to minimize electricity losses and thereby minimize drain on utilities and costs to consumers.

- Reduce harmonics in electrical transmission lines. Chargers can vary current in such a way as to increase energy losses in the electrical distribution system and interfere with control signals the utility sends over its transmission lines.

- Include timers so EHV owners can plug in the charger when they park the vehicle, but delay charging until the hour off-peak rates become applicable.

- Provide interrupt mechanisms. A small radio receiver could accept signals from the utility to automatically turn off the charger during peak loads. Lower electricity rates would probably be offered to persons with interruptable service.

Since chargers must be compatible with the type and size of batteries, charger manufacturing and sales must be coordinated with battery pack manufacturing and sales. Many electric and hybrid vehicles will come equipped with on-board chargers which are compatible with the type of battery in the vehicle. Lead-acid, nickel-zinc, and nickel-iron batteries will use similar chargers, but the amount and rate of charge should be adjusted to the rating of the battery pack to reduce the possibility of damage to the batteries. Lithium-metal sulfide batteries will require chargers which monitor each cell individually, since overcharging any cell can cause severe damage. Zinc-chloride batteries will probably use off-board chargers; these chargers will be larger in size since they must circulate coolant through the battery during recharging.

A charger which operates from a standard 120-volt, 15-ampere household outlet will probably be included with the purchase of an EHV. Such a charger can in 8 hours provide energy for about 35 miles of driving. A more powerful charger which operates from a 220-volt, 30- or 50-ampere outlet (such outlets are found in some homes for use with dryers or electric ranges) might be offered as standard equipment or as an optional extra with EHV purchase. This charger could accept a "quick charge;" i.e., it could provide energy for approximately 100-220 miles of driving in eight hours, or energy for about 50-100 miles of driving in one hour.

5.3.2 Home Recharging Facilities

At-home recharging is the most convenient and least expensive method of recharging personal EHVs, and until EHVs become numerous, will probably be the only recharging means which is readily available. The only equipment required in addition to the charger is an electric outlet accessible to the EHV parking area. The EHV owner may wish to install a high-powered electrical outlet in the parking area so the batteries may be quick charged, and an additional meter so vehicle recharging can utilize off-peak rates for electricity.

The number of vehicles that could be recharged at home is limited by the availability of off-street parking with an accessible electric outlet. In metropolitan areas, where the majority of EHVs would probably be located, between 50 and 85 percent of vehicles can be parked off the street (Table 5.3). However, these include cars at multi-family dwellings which are much less likely than single-family houses to have access to an individually metered electrical outlet. Approximately 60 percent of all cars in metropolitan areas are located at single-family dwellings with off-street parking. If each of these residences had facilities to recharge only one electric vehicle, about 35 percent of

TABLE 5.3

ESTIMATED AVAILABILITY OF CARS AND OFF-STREET PARKING

	United States	Outside SMSAs	In SMSAs* Total	In SMSAs* In Central Cities	In SMSAs* Outside Central Cities	Los Angeles Long Beach SMSA	Washington DC SMSA
Population, thousands	211,391	56,427	154,964	-	-	6,926	3,015
Occupied Housing Units, thousands	70,830	19,586	48,674	22,566	26,109	2,520	981
With Parking, percent	83	77	85	86	84	94	71
Single Family, percent	63	75	61	52	70	61	56
With Parking, percent	78	73	80	80	79	94	54
Multifamily, percent	37	25	39	48	30	39	44
With Parking, percent	91	87	92	93	91	94	93
Persons Per Unit	2.98	2.88	3.18			2.75	3.07
Cars Available (estimate), thousands	85,178	23,321	59,628	23,278	36,778	3,243	1,302
Percent of US Total	100	27	70	27	43	4.6	1.5
Cars Per Occupied Housing Unit	1.20	1.19	1.23	1.03	1.41	1.28	1.33
Cars as Percent of Available Cars							
At 1 Car Units	39.4	44.1	36.9	43.7	32.5	37.1	32.1
Single-Family	24.0	32.9	21.5	22.7	20.8	20.4	14.9
Multi-Family	15.4	11.2	15.4	21.1	11.8	16.7	17.2
At 2 Car Units	45.6	42.2	47.3	43.0	50.2	45.9	48.0
Single-Family	35.0	34.5	36.7	31.5	39.9	34.4	35.3
Multi-Family	10.5	7.5	10.6	11.4	10.3	11.8	12.7
At 3 or More Car Units	15.1	14.0	15.8	13.3	17.3	17.0	19.9
Single-Family	13.0	12.5	13.7	11.1	15.3	14.5	16.9
Multi-Family	2.1	1.5	2.1	2.2	2.0	2.5	3.0
Cars with Parking, percent+	56-83	65-77	52-85	62-86	58-84	67-97	47-71

Source: Current Housing Reports Annual Housing Survey, 1974, Part A, US Department of Commerce, Bureau of the Census, Washington, D.C., 1976.

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*SMSA - Standard Metropolitan Statistical Areas

+Assumes each housing unit with parking has either one space (lower limit) or as many spaces as cars available (upper limit).

all cars in metropolitan areas (25 percent of all cars) would have easy access to recharging facilities.[3] These percentages may rise slightly in the future since many metropolitan areas require that new housing units include off-street parking areas.

During the construction of a single-family dwelling, the individual cost of installing an additional high-powered (e.g., 250-volt, 50-ampere) outlet for EHV recharging would be modest, about $100. Installing additional equipment and extending the wiring in existing single-family dwellings would cost approximately $300 (Table 5.4). Electric companies provide meters free; however, they would probably charge for an additional meter to monitor off-peak electricity use (e.g., Potomac Electric and Power Company currently charges $2 per month for off-peak meters.

The costs for the installation of electric outlets for multi-family dwellings include individual meters, circuit breaker panels, and outlets. The cost per stall is estimated to be about $400 for covered parking and $500 for uncovered parking[4] (Table 5.4). These costs would also apply for installing recharging facilities in commercial garages.

Because of the greater convenience and lower cost of recharging at single-family dwellings, these households are the most likely candidates for EHV ownership, at least initially. In major cities, many vehicles are parked in apartment or commercial garages. Private and public sector EHV policies which encourage the installation of recharging facilities in multi-car garages would open the opportunity to urban apartment dwellers for EHV use.

5.3.3 Recharging Away From Home

There are a number of methods and facilities for recharging away from a vehicle's home base, such as biberonnage (recharge from electric outlets at parking places in commercial and industrial parking lots, at on-street parking places, or in municipal parking lots), quick-charge service stations, battery exchange stations, and electrified highways. Such facilities would provide the same refueling service to electric vehicles[*] as gas stations provide to conventional vehicles. The ability to recharge away from home would help remove the range limitation, one of the main obstacles to widespread acceptance of electric vehicles. Gas station owners, battery manufacturers, electric utilities, commercial businesses, employers, and government agencies could all become involved in the implementation of these facilities, but whether profit

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[*] Since the range of hybrid vehicles is not limited by battery charge, away-from-home recharging is not necessary, although hybrid vehicles may make use of these facilities.

TABLE 5.4

COST OF HARDWARE AND INSTALLATION FOR ELECTRIC OUTLETS FOR RECHARGING

(Outlet Rating: 240 Volts, 50 Amps Maximum)

	Covered	Uncovered[1]
Single-Family Dwellings[2]		
From meter through outlets		
New Construction	$ 90	$105
Existing Construction	293[3]	271[4]
Multi-Family Dwellings or Parking Lots		
Cost per stall including individual meters[5]		
New Construction	392	497
Existing Construction	392	508

Source: W. C. Harshbarger, Installation Costs for Home Recharge of Electric Vehicles (Draft), General Research Corporation RM-2291, January 1980.

Assumptions:

1. Includes locking, waterproof covers on outlet.
2. Cost of meter not included.
3. Circuit breaker panel mounted on interior wall, extend existing wiring through walls.
4. Circuit breaker panel mounted on exterior wall.
5. Based on a line of ten stalls; includes individual meters, circuit breakers, and outlets.

will be a sufficient motivating factor is unknown. Although the convenience of being able to refuel during trips may be appealing to electric vehicle owners, charging during peak daytime hours could overburden utilities. The extensive requirements for facilities and their high cost may be an important obstacle to the implementation of away-from-home recharging, at least until a high level of electric vehicle penetration is reached.

Biberonnage refers to the practice of recharging an electric or hybrid vehicle whenever it is parked away from its home base. The battery could be "topped off" or partially recharged over short periods of time at numerous locations. An on-board charger would be a necessity, as would be electric outlets at many parking places. The concept is similar to the practice in very cold climates of providing electric outlets in parking places so heaters may be used to prevent the engine block from freezing. The costs for installing recharging facilities would be roughly $500 per outlet, similar to that for installations in apartment parking lots and garages (Table 5.4). In addition to commercial garages, electric vehicles could conceivably be parked by a parking-meter type of device into which coins could be deposited for electricity delivered.

A first step to biberonnage would probably be the provision of recharging facilities by employers so that their employees could recharge their electric vehicles for the return home. However, since the majority of people work during the day, off-peak electricity rates would not apply, making recharging at work more expensive and more burdensome on electric utility capacity than recharging overnight at home. Recharging facilities for visitors in commercial districts might be supplied by businesses to attract shoppers. Local governments might supply recharging facilities in municipal parking lots to encourage EHV use downtown.

Another possibility for range extension is quick-recharge service stations. It is possible to recharge a fully-discharged propulsion battery to 50-60 percent of its capacity in an hour or less; exact times and amounts depend on the type of battery. A quick-charge station could then provide enough energy during a lunch hour, a business meeting, or a shopping excursion to increase the effective daily range of an electric vehicle by 50 percent or more.

To accept a quick charge, an EHV would have to be equipped with a 220-volt charger or, if the vehicle was of a standard design, the on-board charger could be bypassed and the station's charger used.

Quick-charge stations could be located in regular gas stations, but special facilities with high electrical capacity would be essential. An 80-percent recharge in 45 minutes would require over ten times the average power for an overnight recharge. Due to the high cost of special facilities, operating personnel, peak-hour electricity rates, and business profit, a quick charge would be much more expensive than an overnight recharge at home. Therefore drivers of electric cars would be unlikely to incur the expense and inconvenience of quick charges except when essential to their travel plans. If electric cars achieve their projected ranges, the need for quick recharges would be infrequent, generally only on intercity trips. In consequence, quick-recharge stations are unlikely to be as common as today's gas stations.

A third facility which could provide range extension is a battery swapping station. With proper design, a depleted battery pack can be removed from a car and replaced with another fully-charged battery in two or three minutes. The effect is to make refueling as quick and easy as for conventional cars.

Battery swapping imposes a number of restrictions on electric vehicles. First, the vehicles must be designed so that the battery can be easily removed, yet be safely contained in collisions. Second, the battery sizes must be standardized so that stations do not have to stock a wide variety of battery packs to fit different cars. Third, the leasing of batteries, as opposed to outright ownership, is essential. Otherwise the user could not safely trade his battery for another which might be near the end of its life, and consequently of much less value. Swapping stations, perhaps in conjunction with battery manufacturers, would necessarily be involved in lease administration. One advantage of battery leasing is that it lowers the initial price of an EHV, spreading battery equipment costs over the life of the vehicle. On the other hand, it introduces administrative expenses beyond those of simple ownership.

The cost of a battery swap has been estimated to be between $4 and $7, depending on the size and location[*] of the station.[5] This is much more than the cost of a home recharge because of the cost of facilities, equipment, battery stocks, and personnel; but it may be a reasonable price to pay for extending range by a hundred miles. The swap cost would certainly be less than the cost of renting a conventional car for the occasional long trip.

A very different concept of providing range extension to electric vehicles and decreasing the gasoline use of hybrid vehicles is electrified highways, which electromagnetically transfer energy to vehicles. An electrified highway would have a power strip installed flush with the road surface in the center of one lane. The power strip safely carries an alternating electric current which produces a magnetic field. When an electric vehicle equipped with a power pickup drives over the power strip, the energy is magnetically coupled through a clearance gap between the source and the pickup device. The batteries are recharged while driving over the power strip, and the stored energy can be used for travel on non-electrified roads.

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[*] Land costs are a significant portion of facility costs, and are usually much higher at access points to busy freeways than along minor highways.

A study of an electrified highway system estimates that the power pickup would add about $300 to the cost of an EHV.[6] The roadway power source, including installation in an existing highway, is estimated to cost nearly $350,000 per lane-mile. However, it would only be necessary to equip a few heavily traversed major routes with the roadway power system to provide area-wide service with electric or hybrid vehicles.

Electrified highways are amenable to the inclusion of automatic vehicle controls. The magnetic field from the roadway power source can provide guidance and transmit other data to vehicles. Automatic vehicle control appears to be a feasible means of achieving large increases in the capacity of existing highway systems.[7] Controlled vehicles could in theory be safely operated at high speeds with short headways.[8] These concepts are in the preliminary stages of development. Since the public has demonstrated a strong preference for individual automotive transportation over mass transit systems, yet is reluctant to fund new highway construction, increasing the capacity of existing highways becomes increasingly important. Electrified highways could provide dual benefits of providing range extension for EHVs and guidance control for all vehicles.

5.4 MATERIALS

5.4.1 Materials Required for Automobiles

Since many similarities exist between electric and hybrid vehicles and conventional cars, a shift to EHVs would affect materials usage only to the extent that the electric motor, controller, and battery differ from the internal combustion engine system of a conventional vehicle.

The primary materials used in typical present-day automobiles are steel and cast-iron, plus aluminum, rubber, plastic, and other nonmetals (Table 5.5). Future automobiles will require considerably less material overall, with higher proportions of light materials, such as aluminum and plastic, increasing their shares from 6 percent to 12 percent and 7 percent to 9 percent of vehicle weight, respectively. EHVs will require greater amounts of structural materials (30 to 70 percent more structure and weight in near-term electric vehicles, depending on battery type) to carry the added weight of the batteries. However, since autos are rapidly being downsized, thereby using less structural material, a switch to EHVs will slow the rate of decrease, rather than increase, the consumption of structural materials.

TABLE 5.5

MATERIALS IN TYPICAL US AUTOS, 1980 AND 1990

	Weight, lb		percent	
Material	1980	1990	1980	1990
Steel	1600	1368	56.9	54.2
Cast Iron	384	200	13.6	7.9
Aluminum	178	299	6.3	11.9
Copper, Brass	27	14	1.0	0.6
Zinc	12	8	0.4	0.3
Lead	22	18	0.8	0.7
Other Metals	20	35	0.7	1.4
Rubber	144	128	5.1	5.0
Glass	74	70	2.6	2.8
Plastic	188	231	6.7	9.2
Other Non-Metals	167	151	5.9	6.0
Total	2816	2522	100.0	100.0

Source: R. W. Roig et al., Impacts of Material Substitution in Automobile Manufacture on Resource Recovery, Vol. 1, Results and Summary, US Environmental Protection Agency, Office of Research and Development, EPA-600/5-76-007a, July 1976.

The electric motor which replaces the gasoline engine will be made largely of iron and steel, like the conventional engine. It will, however, include windings of copper wire weighing perhaps 55 pounds for a typical 330-pound motor.[9] This is considerably more than the copper content of automobiles today, and might double the copper content of the average car. The US auto industry now uses about 8 percent of all the copper consumed in this country. Thus, the maximum effect, assuming a complete shift to electric cars, would be to increase copper demand less than 10 percent. If EHV production built up over a period of years, the additional copper requirement would have little effect on production or on reserves and resources.

5.4.2 Materials Required for Batteries

Depending on the type of battery, large quantities of chlorine, graphite, iron, lead, nickel, sulfur, and zinc will be used, plus smaller quantities of aluminum, boron, cobalt, copper, lithium, and potassium (Table 5.6). These materials, plus (in some cases) hydrogen

TABLE 5.6

BATTERY MATERIALS REQUIRED FOR A REPRESENTATIVE FLEET OF ELECTRIC AND HYBRID VEHICLES

	Average Amount of Battery Materials Required per Car, lb								
	Near-Term Batteries						Advanced Batteries		
	Lead-Acid		Nickel-Iron	Nickel-Zinc		Zinc-Chloride*	Zinc-Chloride*	Lithium Metal Sulfide	
Material	EV	HV	EV	EV	HV	EV	EV	EV	HV
Aluminum								56	28
Boron								2	1
Chlorine						57	52	121	61
Cobalt			8	14	11				
Copper			41	6	5			15	8
Graphite						129	92		
Iron			127					62	31
Lead	956	723							
Lithium			4					29	15
Nickel			164	264	207				
Potassium			69	73	57			55	28
Sulfur	153	116						39	20
Zinc				160	125	55	55		
Battery Weight	1580	1195	1055	890	696	840	599	440	221

Source: M, K. Singh and W. J. Walsh, Electric, Hybrid and Baseline Conventional Material Characteristics (Draft), Transportation Energy Systems, Argonne National Laboratory, April 1978, Table 1.

*Source: H. Catherino et al., Cost Analysis of 50 kWh Zinc-Chlorine Batteries for Mobile Applications, COO-2966-1, US Department of Energy, Division of Energy Storage Systems, January 1978.

and oxygen, make up over 95 percent of the weight of each battery. Some batteries may also use small amounts of such materials as antimony and yttrium, but it is possible that other materials could be substituted. Projected requirements are approximate, and could differ considerably in the battery designs which may eventually prove most satisfactory.

5.4.3 Demand for Battery Materials

Demands for materials to manufacture batteries for EHVs will increase the existing and projected demand for these materials. Every battery type requires quantities of at least one material which will significantly affect demand. The percent increases in the baseline primary (newly-mined) demand for battery materials sufficient to electrify 20 percent of the light-duty vehicular travel are shown in Table 5.7. The greatest increases in demand would be experienced if enough electric vehicles to electrify 20 percent of light-duty vehicular travel were built in 1985; the effects of EHV manufacture decrease in later years as the baseline demand rises. In 1985, EHV manufacture could increase the demand in the United States for graphite over 65 percent, the demand for cobalt and nickel 30 to 50 percent, the demand for lead 30 to 40 percent, and the demand for lithium almost 30 percent. The increase in the United States' baseline demand for any of these materials is less than 30 percent by the year 2010. The production of lithium-metal sulfide batteries will more than double the United States' demand for lithium in the year 2000 if enough electric vehicles are manufactured to electrify 20 percent of the light-duty vehicular traffic. The effect on world demand is much smaller. In the near term, the increase in world demand for any material is less than 20 percent, 10 percent in the long term, except in the case of lithium where world demand could increase by as much as 50 percent.

For a given level of travel electrification, hybrids affect material demands less than electric vehicles because they require smaller batteries.

5.4.4 Adequacy of Battery Material Resources*

The extraction of materials for the purpose of manufacturing batteries will deplete considerable portions of the known deposits of some

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*Resource: A concentration of material in the earth's crust naturally occurring in such form that economic extraction is currently or potentially feasible.
Reserve: That portion of the resource from which a usable material can currently be economically and legally extracted.
Identified Resource: Specific bodies of mineral-bearing materials whose location, quality, and quantity are known from geologic evidence supported by engineering measurements.
Potential Resources: Unspecified bodies of mineral-bearing material surmised to exist on the basis of broad geologic knowledge and theory.

TABLE 5.7

PERCENT INCREASE IN PRIMARY DEMAND FOR BATTERY MATERIALS DUE TO ELECTRIFICATION OF 20 PERCENT OF LIGHT-DUTY VEHICULAR TRAVEL

	Percent Increase in Projected Baseline Primary Demand															
	1985				1990*				2000				2010*			
	US		World		US		World		US		World		US		World	
Battery and Material	EV	HV	EV	HV	EV	HV	EV	HV	EV	HV	EV	HV	EV	HV	EV	HV
Near-Term Batteries																
Lead Acid:																
Lead	40	30	9	7	37	28	8	6	31	24	6	5	27	21	5	4
Sulfur	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nickel-Iron:																
Cobalt	27		10		25		8		18		6		15		5	
Copper	1		0		1		0		1		0		0		0	
Iron	0		0		0		0		0		0		0		0	
Lithium	29		15		22		11		14		7		11		5	
Nickel	32		8		27		7		21		5		18		4	
Potassium	n/a		n/a		n/a		n/a		n/a		n/a		n/a		n/a	
Nickel-Zinc:																
Cobalt	50	39	17	13	44	34	14	11	32	25	10	8	26	20	8	6
Copper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nickel	51	40	12	10	44	34	11	8	34	27	8	7	28	22	7	5
Potassium	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Zinc	4	3	1	1	3	3	1	1	3	2	1	1	2	2	1	0
Zinc-Chloride:																
Chlorine	0		0		0		0		0		0		0		0	
Graphite	66		10		60		7		50		5		43		4	
Zinc	1		0		1		0		1		0		1		0	
Advanced Batteries																
Zinc-Chloride:																
Chlorine									0		0		0		0	
Graphite									36		4		31		3	
Zinc									1		0		1		0	
Lithium-Metal Sulfide:																
Aluminum									0	0	0	0	0	0	0	0
Boron									0	0	0	0	0	0	0	0
Chlorine									0	0	0	0	0	0	0	0
Copper									0	0	0	0	0	0	0	0
Iron									0	0	0	0	0	0	0	0
Lithium									104	54	48	25	76	40	35	18
Potassium									n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Sulfur									0	0	0	0	0	0	0	0

Source of Baseline Demand Figures: US Bureau of Mines, Mineral Facts and Problems, 1975 Edition, US Government Printing Office, 1976.

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*Interpolated and extrapolated from 1985 and 2000 data.

materials. Depending on the type of battery, over 30 percent of the United States' reserves of lead and cobalt would be used in the number of EHVs which would serve to electrify 20 percent of the light-duty vehicular travel in the United States. The United States does not currently produce nearly enough of the nickel required for nickel-iron or nickel-zinc batteries or enough graphite for the zinc-chlorine batteries. The advanced lithium-metal sulfide battery will require almost twice as much lithium as is projected to be in the United States' recoverable reserves by 2010; the requirement equals nearly 70 percent of the United States' resources.

Twenty percent of light-duty vehicular travel in the United States could be electrified without using more than 7 percent of the world's identified resources of any single material, except in the case of lithium for advanced lithium-sulfur batteries. These batteries could use up over 30 percent of the world's lithium resources to power EHVs.

Table 5.8 shows how the cumulative demand for these materials from 1974 to 2010 compares with the 1974 reserves and resources, both without EHVs and with electric or hybrid vehicles. The 1974 US reserves cannot provide enough of any material except boron (and lead in the absence of EHVs). Even the 1974 world reserves would be insufficient except for cobalt, iron, nickel, and aluminum. Cobalt supply has an additional problem--it is produced primarily as a byproduct of copper mining, so its availability may be limited by the amount of copper mined. However, cobalt may also be extracted from nickel byproducts, so increased mining of nickel for batteries may increase the amount of cobalt available.

The United States could most readily supply the materials needed for lead-acid batteries, but it is unlikely that the availability of resources will be a constraint on the production of any of the batteries considered here.

The increasing demand for battery materials will be a strong incentive for the development of identified resources. With these, the US could meet its demand for all materials except aluminum, lithium, and sulfur. The United States has only small reserves of bauxite, the main source of aluminum at the present time. However, the United States has large resources of other aluminum sources such as the kaolin-type clay which could meet most of its aluminum raw material needs if the technology is developed. Sulfur can be recovered from secondary sources, such as power plant desulfurization procedures necessary to comply with environmental regulations. The current demand for lithium is very small, so there has been little incentive for exploration. Identified reserves and resources of lithium seem likely to be only a small fraction of deposits actually available in the earth's crust, and increased demand will encourage exploration for new deposits.

TABLE 5.8

ADEQUACY OF BATTERY MATERIAL RESOURCES WITH AND WITHOUT 20 PERCENT ELECTRIFICATION OF LIGHT-DUTY VEHICULAR TRAVEL

	Cumulative Primary Demand 1974-2010 as a Percent of 1974 Resources[1]											
	Recoverable Reserves[2]						Identified Resources[3]					
	US			World			US			World		
Battery & Materials	w/o EVs	with EVs	with HVs	w/o EVs	with EVs	with HVs	w/o Evs	with Evs	with HVs	w/o EVs	with Evs	with HVs
Near-Term Batteries												
Lead-Acid:												
Lead	82	117	108	134	147	144	40	58	54	67	73	72
Sulfur	299	300	300	163	163	163	109	110	109	60	61	60
Nickel-Iron:												
Cobalt	114	146		77	83		77	99		44	48	
Copper	139	140		136	136		31	31		30	30	
Iron	107	107		34	34		24	24		16	16	
Lithium	118	147		106	118		42	52		37	42	
Nickel	5870	7665		79	85		78	102		39	41	
Potassium	N/A	N/A		N/A	N/A		N/A	N/A		N/A	N/A	
Nickel-Zinc:												
Cobalt	114	168	156	77	88	86	77	114	106	44	51	49
Copper	139	140	140	136	136	136	31	31	31	30	30	30
Nickel	5870	8760	8135	79	89	87	78	117	109	39	43	42
Potassium	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Zinc	182	189	188	145	146	146	70	73	72	23	23	23
Zinc-Chloride:												
Chlorine	A	A		A	A		A	A		A	A	
Graphite	722	1058		344	372		43	72		11	12	
Zinc	182	185		145	145		70	71		23	23	
Advanced Batteries												
Zinc-Chloride:												
Chlorine	A	A		A	A		A	A		A	A	
Graphite	722	1058		344	364		43	64		11	12	
Zinc	182	185		145	145		70	71		23	23	
Lithium-Metal Sulfide:												
Aluminum	5620	5623	5626	46	46	46	1124	1127	1125	28	28	28
Boron	46	47	46	35	35	35	46	47	46	35	35	35
Chlorine	A	A	A	A	A	A	A	A	A	A	A	A
Copper	139	140	140	136	136	136	31	31	31	30	30	30
Iron	107	107	107	34	34	34	24	24	24	16	16	16
Lithium	118	315	219	106	192	151	42	111	77	37	68	53
Potassium	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sulfur	299	299	299	163	163	163	109	109	109	60	60	60

Source: US Bureau of Mines, Mineral Facts and Problems, 1975 Edition, US Government Printing Office, 1976.

N/A = Data not available

A = Adequate

Numbers greater than 100 indicate that 1974 resources or reserves are inadequate to supply all required materials.

NOTES:

1. Resource: A concentration of material in the earth's crust naturally occurring in such form that economic extraction is currently or potentially feasible.
2. Reserve: That portion of a resource from which a usable material can currently be economically and legally extracted.
3. Identified Resource: Specific bodies of mineral-bearing material whose location, quality, and quantity are known from geologic evidence supported by engineering measurements.

To some extent this may be true of other battery materials as well. Potential US nickel reserves may be over 800 times as large as known reserves. For nickel, zinc, and lithium, potential reserves are much larger than known resources, and world-wide they are vastly more than would be required to electrify all US automobiles and still produce enough material to satisfy the projected demand for other uses. Increased demand will encourage increased production of identified resources and exploration for new reserves. Beyond potential reserves, there are presumably resources which are subeconomic at present prices with present methods of extraction which might become available if increasing demand causes a price increase sufficient to make extraction of these resources economical.

5.4.5 Recycling

Initially, materials for batteries will come from primary (i.e., newly mined) sources. However, the size of the EHV fleet will eventually stabilize; then additional primary resources would be necessary only to the extent that materials were lost in recycling and manufacturing. The recycling of lead from automotive batteries has been estimated at over 80 percent.* For most future batteries, recycling processes have yet to be developed, but they are expected to be very efficient, with recovery rates well over 90 percent. In consequence, the eventual effects of recycling losses on primary resources would be relatively small. Significant quantities of battery materials would need to be derived from primary sources only for the production of the initial fleet. Recycling facilities will be built when recycling becomes more cost effective than the extraction of raw materials, but recycling should be encouraged both to slow the depletion of natural resources and to minimize the environmental problems associated with the disposal of used batteries.

5.5 PRODUCTION AND SUPPORT

The EHV industry is currently in its infancy, as were today's automobile and aircraft industries in 1900-1910 when horseless carriages and flying machines were being produced by hand in limited quantities. Today's EHV industry consists primarily of small businesses which are pioneering development on a very small scale. Currently about 20 firms are manufacturing electric vehicles, producing less than 10,000 vehicles in 1980.[10] Unlike the major automobile manufacturers, these businesses are very limited in the expertise and resources they can devote to the design and test of vehicles, have very low production capacities, and very little experience in providing parts and service. However, if EHVs are going to replace any significant number of conventional vehicles in the near future, the production and support of EHVs will be accomplished by the major automobile manufacturers who do have the necessary capabilities. In 1979 the United States ICE auto industry produced nearly 8.5 million cars in nearly 4000 manufacturing plants which were sold and serviced at over 20,000 dealers. A total of over one half million establishments are involved in the sales and servicing of these vehicles.[11] General Motors is planning to market an electric vehicle in 1984, and other large companies (General Electric, Chrysler, Gulf & Western, etc.) are developing EVs.

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*The rate would be higher if more batteries were returned for recycling.

5.5.1 Production

Electric vehicles will differ from future conventional vehicles primarily in the drive train and power supply. Hybrid vehicles will have the major components of internal combustion vehicles plus an electrical propulsion system. The body and accessories of EHVs will be essentially the same as conventional cars. Since there are great similarities among all the types of vehicles, most of the manufacturing plants, materials, and operations will be unchanged. Expansion in various industries will be required in the industrial capacity to produce motors, controllers, and chargers. Major impacts will occur in the battery manufacturing and recycling industries.

The major constraint to the immediate manufacture of substantial numbers of electric or hybrid vehicles is the lack of capacity for battery production. A sizable lead-acid battery industry exists for starting, lighting, and ignition batteries or golf-cart propulsion, but this battery is not appropriate for electric or hybrid vehicles. But at least the basic production techniques and bases for expansion exist. Other types of batteries are only produced in limited quantities or are in the experimental stages. Some require special handling techniques, such as the high-temperature lithium-metal sulfide batteries, which could make production more difficult. Gearing up for production of these batteries would take a number of years.

The manufacturing of hybrid vehicles would require the use of the same facilities and personnel as the manufacturing of conventional vehicles, since hybrids will also contain an internal combustion engine, although it will be smaller. The automotive industry will have to retool, to some extent, to produce the modified equipment, but the industry periodically retools to produce new vehicle lines in any case.

The manufacturing of electric vehicles would have a greater effect than hybrids on the production facilities of automotive industries since the equipment and personnel involved in the manufacturing of the internal combustion engine will no longer be required.

Both electric and hybrid vehicles will require motors, controllers, and chargers. Expansion of the electric motor production plants and the construction of facilities to produce controllers and on-board chargers will require some time and capital investment, but no obstacles to producing these parts are foreseen, especially if increases in electric and hybrid vehicle penetration are gradual, over a period of ten years or so.

The motors required for EHVs are not significantly different from electric motors now produced, although new motors will probably be specifically designed to fit the needs of electric and hybrid vehicles. A large electric motor manufacturing industry already exists, and with some expansion should easily be able to produce the required quantities. As the major motor vehicle manufacturers begin to produce significant numbers of electric and hybrid vehicles, they will most likely begin to make the motors themselves since the production requires techniques similar to those for the production of conventional vehicle parts.

The electronics industry has expanded enormously in recent years. Although EHV controls would be a new product, the industry should be able to design and produce suitable equipment. Again, the automotive industry will probably produce electric and hybrid vehicle controls, since they already produce other types of electronic devices.

Battery chargers such as those used to recharge starting, lighting, and ignition batteries and forklift batteries are currently being manufactured; but, due to their size and low efficiency, they are not very well suited to recharging electric and hybrid vehicles. Little attention has been paid to designing a suitable charger for electric and hybrid vehicles, but the technology is available, and their production should not cause any major problem (see Sec. 5.3.1).

Once substantial numbers of electric or hybrid vehicles are in use, a recycling industry must be functioning to cut down on the requirement for primary materials. Only lead-acid batteries are currently recycled. As yet, techniques have not been developed for recycling most other batteries. However, the recycling industries would have a longer lead time to develop processing capacity than the actual vehicle production industries would have. A recycling industry would develop if recycling is more economical than extraction, but the costs are unknown. In any case, recycling should be encouraged because of the environmental hazards of resource depletion and waste disposal.

5.5.2 Support

After EHVs leave the factory, they are distributed, marketed, sold, maintained, and repaired. The major auto manufacturers already have a large nationwide infrastructure for these purposes, but small vehicle manufacturers currently have little or no support for their products.

The Department of Energy is sponsoring a demonstration program in which some 500 EHVs are operating at a number of sites across the country. The current DOE demonstration program is encountering problems associated with the repair and maintenance of EHVs. However, these current problems stem primarily from the limited capabilities of the small manufacturers providing the vehicles. They are not inherent in EHV technology, which has the clear potential to reduce service requirements and improve vehicle reliability. By 1984, when GM has announced it expects to market an EV, their resources and expertise with mass production, distribution, and associated maintenance should minimize the problems presently encountered by the small manufacturers. With proper design and test, parts supply, and personnel training, all of which are routine for large manufacturers, few problems should arise. Electric drive is inherently simple and in its few vehicular applications (industrial lift trucks, London's milk delivery vehicles) has been relatively trouble-free. Although hybrids will be complicated by the interface with an ICE, the engine itself will be smaller and simpler than conventional engines, and will be used less.

Maintenance of EHVs will also be enhanced because electric motors, controllers, chargers, and battery-related parts may be more reliable and simpler than those of an ICE. Electric highway vehicles now being built have been no more reliable than conventional ICE vehicles, but this appears to be primarily the result of inexperience and very small-volume production without the extensive testing and design verification which precedes high-volume production. In addition, much of the power system will consist of solid-state electronic components. Maintenance of these devices is generally limited to fault detection and module (circuit board) replacement rather than complete disassembly and repair. This should provide a major benefit, in terms of maintainability, and the cost should not be excessive since the price of electronic equipment has dropped drastically in the past few years. Complex control electronics, furthermore, are not a unique problem of EHVs: every GM car in 1981, for example, includes electronic engine controls directed by a microcomputer, and computerized instrument panels are likely to follow soon in many car models.

Another potential problem area is the time lag between the introduction of new technology vehicles and the ability of private maintenance shops to service these vehicles. It currently takes about one year before motor manual publishers produce and distribute appropriate maintenance literature. However, this time period generally coincides with the dealer warranty period, which tends to minimize any initial problems.

Any new technology will cause some problems for its users until the "bugs" are worked out of the designs and production techniques, and until maintenance personnel gain experience with the new systems. However, if the massive infrastructure which is already in place is used to supply training and parts for EHVs, rather than the current small EHV producers building their own infrastructure, satisfactory support of EHVs could be accomplished in the minimum time.

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6 MARKETABILITY

6.1 SUMMARY

In the coming decade, electric vehicles will probably offer sufficient range and performance for most urban travel by personal vehicles. Near-term hybrid vehicles will probably be adequate not only for most urban travel, but for most long-distance trips as well. From limited survey data on vehicle use, it appears that electric cars with a 100-mile range could electrify about 80 percent of the annual travel distance of the average US automobile. Hybrids with a 60-mile useful electric range could probably electrify an equal amount, because they could be used on long trips which electric vehicle owners would make entirely by an alternate ICE vehicle.

Nevertheless, market penetrations for electric and hybrid vehicles are generally expected to be modest. Projections produced by several independently-developed econometric models indicate market shares in the mid-1990s of 1-10 percent, despite major advances in technology and the advent of mass-produced EHVs in auto showrooms. The projections, however, are generally based on assumptions that real prices for gasoline and electricity remain little changed. Under these conditions, the reduction of operating costs offered by EHVs is insufficient to offset their higher initial prices and limited capabilities, at least for the great majority of motorists.

The key uncertainty in such projections is the future price and availability of gasoline in future years. Though EHV technology improvements are unlikely to suffice for substantial market penetration, future EHVs could capture far more than 10 percent of the market if interruptions in the supply of motor fuel recur, or if motor fuel prices rise rapidly in relation to electricity prices and the overall price level. As of late 1980, however, such price trends were not clearly established.

The US Government is seeking to enhance the competitive position of electric cars by subsidizing research, development, and demonstration (RD&D) of new technology and by supporting fledgling EHV manufacturers. Even if the RD&D is successful, however, major additional governmental incentives would probably be necessary to obtain an EHV market share exceeding a few percent, unless gasoline becomes relatively scarce and expensive in relation to electricity. Projections of EHV market share versus relative gasoline price are not available.

6.2 VEHICLE USE

Personal automobiles have brought Americans unparalleled mobility, and with it the ability to choose among a wide variety of residential settings and job opportunities, and to participate in a broad spectrum of social, educational, recreational, religious, and cultural activities. With good reason, the American motorist seeks to preserve this mobility even as resources of petroleum dwindle. To examine his willingness to purchase an electric vehicle, then, it is necessary to begin with the kinds of conventional vehicles in use, the travel they provide, and the extent to which this travel might be curtailed by vehicles with limited capabilities.

6.2.1 Types of Vehicles

There are about 146 million light-duty vehicles--passenger cars, light trucks, and vans--in the United States. The days of rapid growth of this light-duty vehicle fleet appear over (Table 6.1); one estimate places the average annual increase at only 0.6 percent per year. Years ago, growth was rapid as more and more families were able to afford automobiles. Now there are nearly as many light-duty vehicles available as there are Americans of driving age.

Passenger cars are expected to constitute roughly 80 percent of light-duty vehicles in the future, as at present.[1] Ninety-one percent of passenger cars are personal vehicles, while the remainder are operated in fleets. In 1979, 56 percent of new passenger cars were domestic subcompacts and compacts, or else imported. Twenty-four percent were intermediates, and only 20 percent were standard or luxury models.[2] The future percentage mix of four- five-, and six-passenger cars will probably move even further towards the smaller vehicles, as it has tended to do over the past decade. This trend tends to favor EHVs, which are more expensive to buy than comparable conventional cars and thus are more likely to be beyond the average family budget unless small.

The trend toward smaller passenger cars has in part been offset by increased personal use of trucks.[3] In the decade 1968-1977, truck sales grew at 6.1 percent per year, versus 3.6 percent per year for passenger cars. This growth was interrupted by motor fuel shortages and price increases largely due to reductions in Iranian production during late 1978 and early 1979; whether it will resume is uncertain. Demand for personal trucks shifted industry output towards the light-duty versus heavy-duty trucks; by 1980, 90 percent of all new trucks were under 10,000 pounds gross weight, versus 77 percent ten years earlier. About 60 percent of all light trucks are in personal use. Most light trucks are pickups, and most of those standard rather than compact in size. Vans account for something under 20 percent of all light trucks, while utility vehicles and other light truck designs account for about 10 percent.

6.2.2 Urban Use of Personal Vehicles

In urban travel, distances are usually shorter than in travel outside and between urban areas. For this reason, it is generally expected that electric cars with limited ranges will be used primarily in

TABLE 6.1

PROJECTED SIZE AND COMPOSITION
US LIGHT-DUTY VEHICLE FLEET

Year	Total Vehicles, millions	Passenger Cars, millions	Light Trucks, millions	Light Trucks, percent
1980	146.1	117.5	28.6	19.6
1985	154.5	122.3	32.2	20.8
1990	161.8	128.0	33.8	20.9
2000	167.6	132.1	35.5	21.2
2010	175.2	136.9	38.3	21.9

Source: Projection of Light Truck Population to Year 2025, ORNL/Sub-78/14285/1, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Assumptions:

- Moderate population growth (US Bureau of the Census, "Series II")
- Moderate economic growth (1 percent per year growth in per capita disposable income)
- Maximum car/population ratio of 0.53 in 1980-1990 (versus 0.50 in 1975), declining to 0.51 in 2000 and 0.50 in 2025
- Termination of the current growth trend in number of light trucks per capita in 1985

urban travel. About three-fourths of the personal cars in the United States are based in urban areas, and about one-third of urban-based cars are second or third cars at multi-car households.[4] These cars are driven much less than the average and might easily be electrified because another car at the household could be used for long distance travel or carrying large loads. The short distances in urban travel are also suitable for electrification by hybrid cars, which must use petroleum fuels only in long-distance travel.

Though average urban travel is undemanding, roughly 20-25 miles per day, most urban cars are driven much longer distances at least occasionally. The critical questions then for EHVs are these: How much of the time would a given electric range suffice for typical EV drivers? What fraction of the total distance driven could hybrids travel on electric power from utilities?

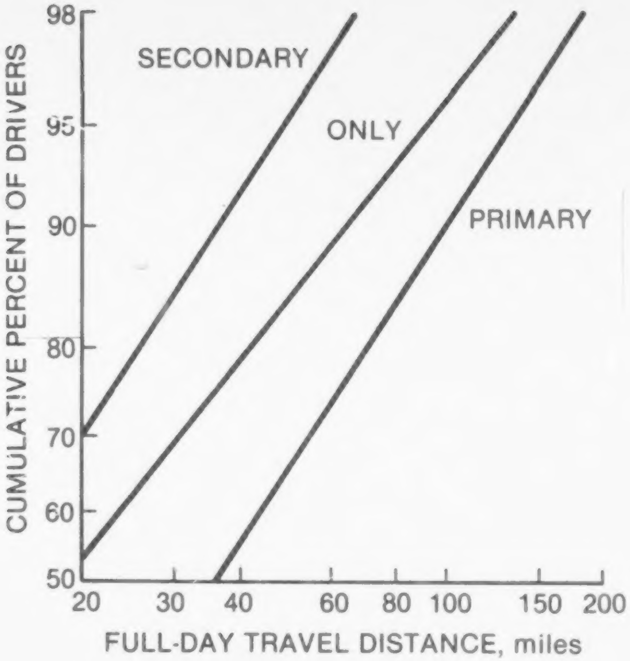
The most useful answers to these questions are based on typical full-day driving, i.e., driving required between overnight recharges. At present, facilities are unavailable for recharges during the day away from home, and it is not clear that they will ever be widely dispersed. Detailed information on full-day travel in two large US cities is available.[4] The data from Los Angeles, a reasonable example which was specifically analyzed for EHV applications, shows:

- At households with only one driver on the survey day, 95 percent of the drivers reported driving less than 93 miles.
- At households with more than one driver, 95 percent of the secondary drivers reported less than 47 miles, while 95 percent of the primary drivers reported less than 137 miles.

The primary driver at each multi-driver household is that driver reporting the greatest total driving distance on the survey day. The secondary drivers were all other drivers reporting driving at these households. These three groups of drivers, only, primary, and secondary drivers, are approximately equal in size. The distances traveled by the vehicles they drove are very close to the distances traveled by the drivers because very few drivers shared a single vehicle on the survey day.

These data give a good picture of travel by many drivers on a single day. They are based on a very large sample, all the drivers at around 30,000 households. It is uncertain, however, what they imply for a single driver during many consecutive days. There is little information to show whether the drivers reporting little total travel on a given day are unlikely to travel long distances on any day, or whether all drivers in a class are equally likely to travel a long distance in a day. The latter has been generally assumed for electric vehicle analyses. Thus it is assumed that an electric car with a range of 93 miles would suffice for 95 percent of the urban travel days of drivers at households with only one driver.

A large increase in range is necessary to make electric cars capable of all driving on 98 percent rather than 95 percent of driving days (3 extra days out of each hundred). For only drivers, the necessary range increase would be 45 percent (from 93 to 135 miles) (Fig. 6.1).



SOURCE: LOS ANGELES ORIGIN-DESTINATION SURVEY, 1967

Primary driver: the driver reporting more travel than any other driver at a multi-driver household

Secondary driver: any driver other than the primary driver at a multi-driver household

Only driver: the only driver reporting travel at a single-driver household

Figure 6.1 Distributions of Full-Day Urban Driving Distance Reported by Major Categories of Drivers

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Because the increase is large it would add substantially to the expense of the electric car; and for only 3 days out of every hundred, the extra expense may not be justified. It appears, for example, that renting an ICE car for long travel days becomes cheaper when electric car range is somewhere between the 95th and 98th percentile requirement of only drivers.[4]

The survey data discussed above is 13 years old and comes from a city long regarded as exceptionally dependent on automobiles. Better data will not become available until a new national survey of similar overall size made during 1977 is completely analyzed. Meanwhile, the Los Angeles results remain useful and probably relevant. There is little reason to expect that there have been large changes in personal vehicle use since 1977: freeway networks changed little in the 1970s, and the average travel per passenger car in the United States in 1978, the most recent year for which data is available, was little more than in 1968 (10,046 versus 9,507 miles). The probable decline in average travel per passenger car since the summer of 1979 has probably brought average travel per vehicle in 1980 even closer to that of the Los Angeles survey. Annual travel per passenger car is among the most stable of national travel statistics: over the 50 years from 1930 to 1980 it has moved within a 6 or 7 percent range around 9,500 miles (excepting only the years of gasoline rationing during World War II). Average travel per automobile in the Los Angeles area, furthermore, is not atypical; in fact, both the survey discussed here and annual estimates reported by the Department of Transportation for California suggest average annual vehicle use in Los Angeles is a little less than the national average.[4]

Survey data from Washington D.C. taken in 1968 shows daily travel distances somewhat below those of Los Angeles. For secondary drivers, the 95th percentile travel distance reported on the survey day was 25 percent less than in Los Angeles, while for primary drivers it was nearly 50 percent less (Table 6.2). Somewhat less travel is to be expected because the Washington area is much smaller physically than the Los Angeles area, so maximum distances of single urban trips are more limited. Furthermore, the central focus of the Washington area is much greater and there was much less freeway available per car, making long trips slower and more difficult. Even so, there remain reasons to question the lesser travel indicated by the Washington survey.[4] In any case, both the Washington and Los Angeles data indicate that to meet the needs of 95th percentile drivers, cars must seat 3 to 4 persons, and that in Los Angeles freeway capability is required. It may still be that substantial percentages of cars could be limited in size and performance to two passengers and slow speeds; but the data suggests that such "urban" cars would be unsatisfactory for the great majority of drivers unless patterns of vehicular use change substantially.

An electric car with 100-mile range would suffice for the travel of households with only drivers on 96 percent of urban travel days, according to the Los Angeles data (Fig. 6.1). The 100-mile range would also have sufficed for 96 percent of all drivers taken together in Los Angeles. This does not imply, however, that the 100-mile electric cars could accomplish 96 percent of the total urban travel of all drivers. Instead, a safer estimate would be 80 percent of all miles driven (Fig. 6.2). Drivers who travel over 100 miles in a day account for a disproportionate fraction of the total distance traveled. If none of them could use an electric car for any portion of their full-day travel, and

TABLE 6.2

NOMINAL REQUIREMENTS FOR PERSONAL URBAN ELECTRIC CARS

(to satisfy 95th percentile requirements)

	Range, miles	Capacity, persons
Secondary Car	35[*]-47[†]	3-4
Only Car	53-93	3-4
Primary Car	68-137	4

Source: W. Hamilton, Electric Automobiles, McGraw-Hill Book Company, New York, 1980.

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[*] Based on Washington, D.C., data from 1968

[†] Based on Los Angeles data from 1967

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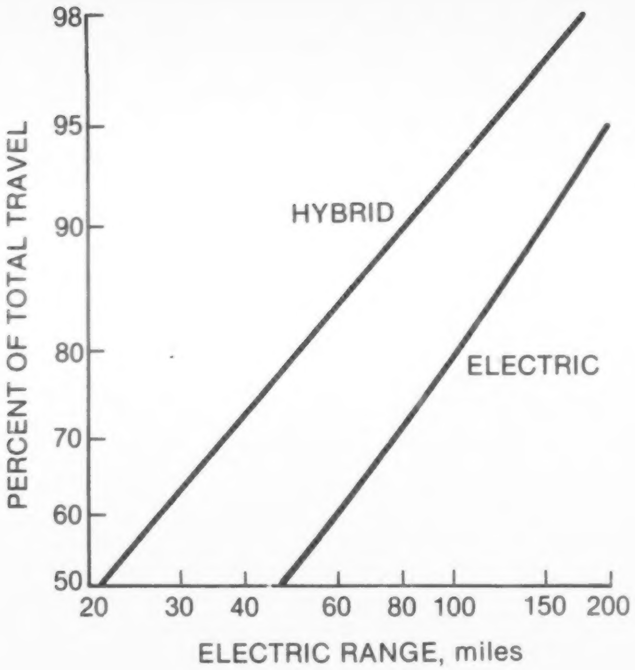
always substituted ICE cars instead, then the 100-mile electric car could electrify about 80 percent of urban travel. If part of these long-distance travel requirements could have been met by electric cars, then the percentage could be as high as 96 percent. It seems unlikely, however, that a driver would take trips such that the full range of the electric car could be entirely used before the switch to an ICE car for the remainder of the day's travel.

The driver of a hybrid car, however, can conveniently utilize the entire electric range of the car before switching to ICE propulsion. Thus a hybrid with 100-mile useful electric range could electrify 96 percent of urban travel, and hybrids with shorter electric ranges could still electrify as much urban travel as the 100-mile electric car (Fig. 6.2).

Electrification has so far been discussed only for average cars (or only cars at one-car households). If used as secondary cars, the 100-mile electric car could electrify almost all urban travel by secondary drivers, but this would amount to less total travel mileage per car then electrifying 80 percent of annual travel by the average car. The reason is that secondary cars travel perhaps 6,000 miles per year,



SOURCE: LOS ANGELES ORIGIN-DESTINATION SURVEY, 1967

Assumptions: Hybrid vehicles electrify the first M miles of full-day travel by all drivers, where M is the useful electric range of the hybrids. Electric vehicles electrify only the full-day travel reported by drivers who traveled less than the maximum electric range of the vehicles.

Figure 6.2 Potential Electrification of Urban Driving by Electric and Hybrid Cars

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compared with 10,000 miles per year for the average car. Because usage of secondary cars is undemanding, electric cars are often advocated for second-car application. On the other hand, second cars today are ordinarily relatively old and inexpensive cars which were not purchased new. Electric cars may be entirely too high-priced for this application, given limited consumer budgets for transportation. It seems more likely that with the advent of EHVs, patterns of use will change, at least at multi-car households where different assignments of trips among household vehicles are possible. In the future, travel may be reassigned to maximize electrification of household vehicle-miles. The ICE car could become the second car; it would be used when the other (electric) car was already busy, as at present, but unlike today's secondary cars it would also be used for long trips because they could not be accomplished by the electric car. Because such changes in usage seem likely, it is most appropriate here to focus on electrification of average car travel rather than secondary car travel.

The percentage of urban travel by the average car which could be electrified by an electric car of 100-mile range probably lies somewhere between the extremes just described (80-96 percent). If the actual percentage were halfway between these extremes, it would be about 85 percent for the 100-mile electric car, about the same as the electrification of urban travel by a hybrid with a useful electric range of some 60 miles.

6.2.3 Overall Use of Personal Vehicles

The addition of long-distance trips, beyond the urban area, to urban travel gives overall travel by personal vehicles. It appears that long-distance trips account for roughly 10 to 15 percent of the total distance travelled by personal vehicles. A large minority of households with personal vehicles, 38 percent, reported no such trips in an entire year (Table 6.3). Households making such trips, however, reported an average of five for the year, with an average distance of 620 miles. Furthermore, 43 percent of the total long-distance travel mileage was in trips of over 1,000 miles and 25 percent was in trips over 2,000 miles.

Long-distance travel is important for electric vehicles because it represents an important component of total personal vehicle travel which they could not accomplish. It would require use of an ICE vehicle--either one rented or available at the household. Hybrids, on the other hand, could accomplish at least the first part of a long trip on stored electric energy. A hybrid with a 60-mile useful electric range would accomplish about 10 percent of total long-trip distance on electric power, assuming no recharges after leaving home. With a 180-mile electric range, the hybrid would accomplish nearer 30 percent of the total long-distance travel on electricity.

Combining long-distance and urban travel electrification gives overall electrification potential for hybrid and electric cars. The biggest uncertainty arises in urban travel. Multi-vehicle households have considerable latitude in how both hybrid and electric vehicles can be affected greatly by the manner in which vehicles are assigned to trips in multi-vehicle households, as well as by the length and number of trips on long-distance travel days.

If the 100-mile electric car or the 60-mile hybrid could each electrify about 85 percent of the urban travel by the average car, then the addition of long-distance travel would reduce total electrification to about 77-78 percent. This would probably be increased in both cases by trip reassignment among household cars to minimize gasoline use.

TABLE 6.3

LONG TRIPS (over 100 miles one-way) BY CAR AND LIGHT TRUCK, 1972

Fraction of US households with car or truck reporting one or more long trips	62 percent
Average number of trips per household reporting long trips	5.0
Average round-trip distance	620 miles

Round-Trip Length, miles	Percent of Trips	Percent of Total Distance
200-400	49	22
400-600	22	17
600-800	10	11
800-1000	5	7
1000-2000	8	18
over 2000	4	25
outside US	2	-

Source: 1972 Census of Transportation, National Travel Survey, Travel During 1972, TC72-N3, US Government Printing Office, Washington, 1973.

Accordingly, a reasonable estimate of electrification for use in this report appears to be 80 percent of average annual vehicle miles traveled, both for the electric car with 100-mile maximum range and the hybrid with a useful electric range of 60 miles.

6.2.4 Non-Personal Vehicles

Light trucks in various non-personal uses have often been singled out as promising candidates for electrification. In such stop-start missions as mail delivery, utility meter reading, and coin telephone servicing, electric vehicles first promise to be cost-effective in the United States.

The only major use today of on-road electric vehicles in the world is commercial, for milk delivery in England. Vehicles are specially built for this purpose, whether they use diesel or electric propulsion, so the electric vehicles compete on equal terms rather than with mass-produced conventional vehicles. In this application, the low speeds, frequent lengthy stops, and short ranges required are easily managed by the electric vehicles, but tend to result in high fuel use and maintenance for comparable diesel vehicles. As a result, the electric vehicles have proven cheaper overall.[5] Conditions for milk delivery in the United States, however, are different and ill-suited to electric vehicles.

Total non-personal use accounts for about 40 percent of all light trucks. Unfortunately, relatively few non-personal trucks are now in the utility services--meter reading, coin telephone servicing--which appear most favorable for electric vehicles, and little change is expected here in the future (Table 6.4). Overall, the total number of utility vehicles which are amenable to electrification may be on the order of 100,000. Postal delivery vehicles (not included in Table 6.4) number a little over 100,000; their stop-start mission makes them amenable to electrification. Taken together, however, utility and postal vehicles which could reasonably be electrified constitute only 2 to 3 percent of non-personal light trucks.

Except in these applications, range requirements for light trucks are quite demanding. Range requirements for personal electric light trucks probably equal those of personal electric urban automobiles. Range requirements for fleet light trucks, based on a survey of fleet operators, are even greater.[6] It appears that electric light trucks with 100-mile range would satisfy the range requirements of under 10 percent of fleet trucks, though this is inconclusive because of the low response rate in the fleet operator survey.

The fleet operator survey also disclosed that requirements for passenger cars operated in commercial fleets are generally demanding as well, not just in terms of range, but also speed and passenger capacity.

TABLE 6.4

APPLICATIONS OF NON-PERSONAL LIGHT TRUCKS

Major Use	Percent 1975	Percent 1995
Agriculture	40	26
Services	18	28
Construction	15	14
Wholesale and Retail Trade	14	17
Utilities	5	6
Manufacturing	3	4
For Hire	1	1
Forestry and Lumber	1	1
Other	3	3

Source: Projection of Light Truck Population to Year 2025, ORNL/Sub-78/14285/1, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

This is corroborated by independent investigations of the willingness of fleet operators to use electrics and EHVs, as discussed below.

6.3 MARKET PENETRATION ESTIMATES

Estimates of market penetration for EHVs are generally unsatisfying because they are based on inadequate and incomplete data. They lend some substance to the obvious inference that cars which cost more and do less are unlikely to capture a large market share. They do not establish, however, whether the market share which will be captured is large enough, 2 or 3 percent, to support mass production and the associated vehicle prices assumed in the estimates. Furthermore, most existing estimates are based on little change in the price and availability of gasoline relative to the mid-1970s.

- SRI International estimated for the Department of Energy that some 3.5 percent of the US light vehicle fleet in 2000 might be electric.[7] The estimate was based largely on supply considerations, i.e., the times required to develop improved technology, demonstrate effectiveness, develop commercial designs, tool up for production, and replace vehicles in the existing fleet. The SRI scenario made generally optimistic assumptions about the process by which decisions to produce are made, including full success for the DOE EHV research, development, and demonstration program by 1985.

- Arthur D. Little, Incorporated, made projections of EHV market penetration for DOE with and without additional government incentives beyond the RD&D program.[8] The ADL projection was based on consumer panel surveys, plus the optimistic assumption that electric vehicles would be mass-produced with effective nickel-zinc batteries in 1983. For personal vehicle sales in 1983, market penetration for electrics was estimated at 0.4 percent, and for hybrids a little under 2 percent. For non-personal vehicles, market potential was investigated through interviews with fleet operators which revealed no "sizeable market" in 1983.

- Cambridge Systematics, Incorporated, estimated market penetration for the Department of Energy using an econometric model of auto choice decisions modified for EHVs.[9] Penetrations of zero to 2.2 percent of sales in the year 2000 were estimated for the "most likely" case, which included an advanced 150-mile electric car with high-temperature battery. In the "optimistic" case, an advanced hybrid tripled market penetration.

- Mathtech, Incorporated, projected electric vehicle penetration into the US vehicle fleet for the Electric Power Research Institute.[10] With an econometric model modified to account explicitly for limited range, plus optimistic assumptions about technology, 9 percent of vehicles were projected to be electric in the year 2000. The technological assumptions were optimistic, however, and the actual effect of range limitation on market penetration was negligible in the Mathtech model.

In short, projections to date suggest that 1 to 10 percent of the US vehicle fleet may be EHVs in 2000. All the projections assume, explicitly or implicitly, conditions more or less like those prevailing in 1980. Only the ADL projections, the most conservative of those noted, utilized any direct information about consumer valuation of operating range and rapid refueling capability.

The ADL Analysis is unique because it obtained explicit information from consumers about the relative values they attached to range, purchase price, and other attributes of electric and hybrid cars. One hundred ninety-three auto owners served on panels of consumers who examined both their own actual driving behavior and the probable characteristics of future electric, hybrid, and conventional vehicles. Thus they understood to some extent the implications of the choices they were asked to make among 16 hypothetical electric, hybrid, and conventional vehicles with various capabilities, limitations, and costs. It would be more satisfactory, of course, to infer consumer preferences from actual purchases in the marketplace. But today's auto market does not include electric and hybrid vehicles, or other vehicles with similar limitations, on any significant scale.

Because of its unique value, the ADL preference data is being reanalyzed by Charles River Associates for the Electric Power Research Institute.[11] Results presented to date are especially useful because they make explicit the tradeoffs which consumers make between driving range, acceleration, seating capacity, price, and annual fuel costs (for electricity or gasoline). These tradeoffs are critical to effective design of electric vehicles as well as to their probable market penetration. The findings show that the average consumer surveyed would pay:

- $2,100 to $3,700 more to avoid 7-hour refueling (or recharge) times (depending on whether vehicle range between refuelings were 200 or 50 miles)
- $6,500 more to increase range from 50 to 200 miles
- $3,900 more to increase maximum speed from 45 mph to 65 mph
- $2,000 more to obtain average rather than low acceleration
- $3,500 more for four seats rather than two
- $2.16 more initially to save $1 annually thereafter in operating costs.

Clearly, the average consumer in the ADL panels values the range and the quick refueling capability of the conventional car very highly, and values speed, acceleration, and capacity sufficiently that in the absence of data to the contrary, it is hard to foresee a major role for a limited-performance two-passenger urban automobile in the future. Such vehicles would, of course, cost less to buy and to operate. It is precisely the costs of purchase and operation, however, which the ADL consumer panels addressed as they expressed preferences among the variety of options described to them. Their concern with range, performance, and capacity are especially noteworthy because all panelists came from two-car households in urban areas with mild climates, and none commuted long distances. Furthermore, they were asked to indicate their preferences among the hypothetical electric, hybrid and conventional cars as a replacement for their second car, rather than for some more demanding application.

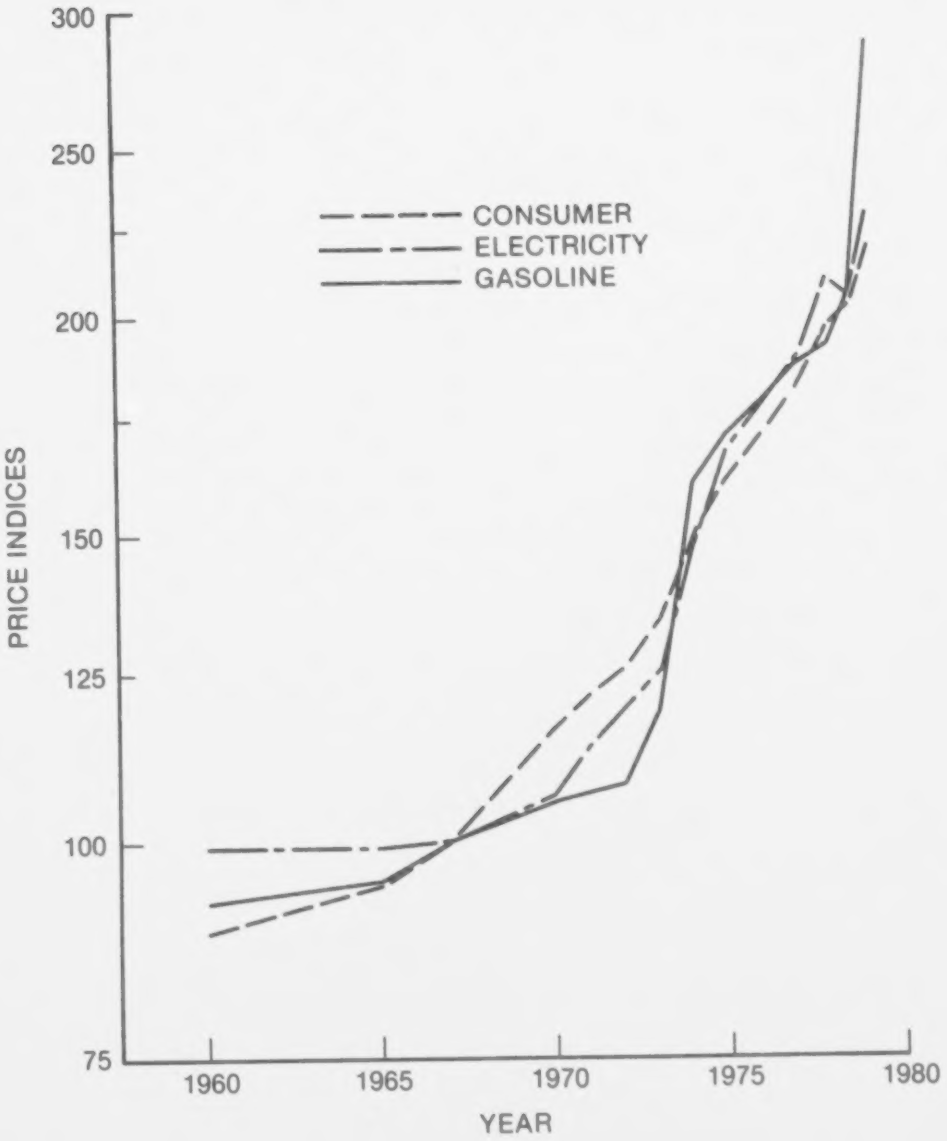
Given the valuations of performance and capability from the ADL Data, summarized above, electric cars can be designed (for a given technology) to offer the best overall combination of range, price, and annual cost for the average motorist. This leads to ranges of 85-90 miles for cars with near-term batteries having the capabilities and costs projected in Fig. 3.10, and 125-150 miles for cars with advanced batteries.

6.4 COST AND AVAILABILITY OF FUEL

The ultimate market potential of EHVs depends greatly upon the relative price and availability of petroleum fuels and electricity. To the extent that gasoline and diesel fuels become more expensive or less available relative to electricity, motorist would have an incentive to switch from conventional vehicles to EHVs.

Since the OPEC oil embargo of 1974, the US has faced unstable energy supplies and much higher prices. Supply disruptions in 1979 focused public concern clearly on the energy issue. The problem has been that over the last decade, petroleum consumption has continued to rise in the United States, but domestic production has remained relatively constant. As a result, it has become necessary to rely on foreign imports to satisfy an increasing share of our demand (48 percent in 1979). Recent disruptions in foreign supply have clearly demonstrated our vulnerability. To some extent, motorists may purchase EHVs as a hedge against further disruptions, even though petroleum fuels may remain as available as they have been in 1980, and no more costly.

The price indices for gasoline, electricity, and all consumer goods have risen at roughly the same rate during the period 1960-1979 (Fig. 6.3). Gasoline prices generally lagged behind electricity prices through 1973, but, as a result of the 1973-1974 OPEC oil embargo, they jumped ahead of electricity prices and the consumer price index. During the following years, gasoline prices fell in relative terms until the Iranian crisis of 1979 led to another abrupt increase. During 1980, gasoline prices have risen much more slowly than electricity prices, which appear to be "catching up" as they did in 1975-1978. At the typical 1980 prices used in this report ($1.25 per gallon, 6 cents per kilowatt-hour average, and 3 cents per kilowatt-hour for off-peak recharging), gasoline has risen about 30 percent relative to average residential electricity since 1967. If this differential increases, EHVs could become important factors in the auto market, in personal transportation, and in the conservation of petroleum.



Source: Statistical Abstract of the United States, US Department of Commerce, Bureau of the Census, 1979

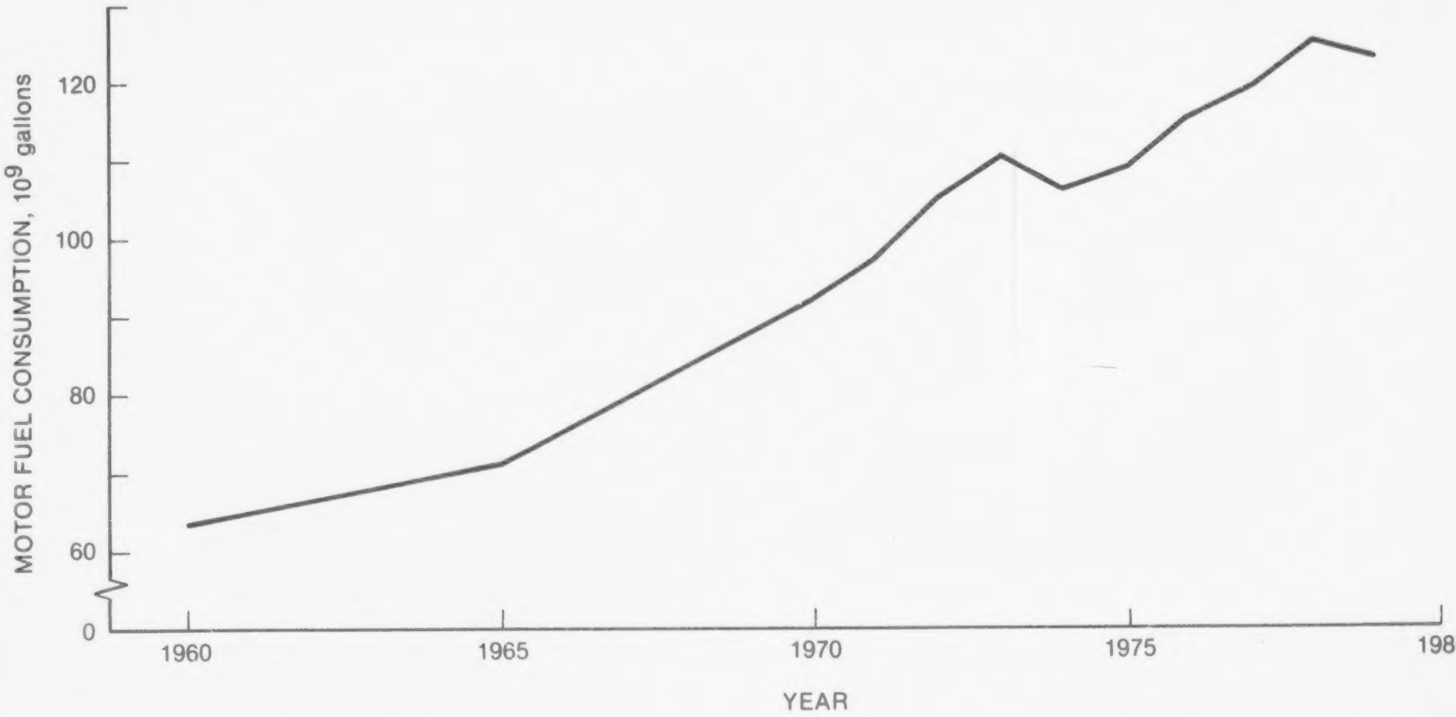
Figure 6.3 Gasoline, Electricity, and Consumer Price Indices, 1960 Through 1979 (average)

Experience during the 1973-1974 OPEC oil embargo and the 1979 disruptions in supply indicates that long lines at service stations--and concern about the unavailability of fuel--may affect motorists more than the price increases accompanying them. Quarterly figures for gasoline prices and sales support this clearly. In fact, the rapid response of the public, in terms of demand, is clearly evident in analyzing annual consumption of all motor fuels, including diesel, since 1960 (Fig. 6.4). Each major crisis was immediately followed by a sharp decrease in consumption. However, in 1973-1974, this sharp decrease was followed by a resumption of normal growth after only about two years. Whether this will happen again as a result of the 1979 crisis is unclear.

Future prices and availability of gasoline and diesel are difficult to predict because they are dependent upon many imponderables, largely government actions, both foreign and domestic. The cutoff of Iranian production, future OPEC price and supply decisions, and the ability of Saudi Arabia and Kuwait to continue stepped-up production to make up for other shortfalls are typical of situations that could have great influence in the future.

The price and availability of electricity is also influenced by increased prices for foreign oil, as well as by increased costs of capital for construction and public resistance to development of new nuclear power plants. Although an average price of 6 cents per kilowatt-hour is used in this report to represent the national average, it is important to note that prices vary greatly from region to region and company to company. This variation is on the order of 8:1.

One means of minimizing the impact of EHVs on the electric utility industry is to make use of existing underutilized capacity, rather than constructing new power plants. This can best be done if recharging is accomplished during off-peak periods. Establishment of low off-peak electricity prices would help to encourage recharging during these periods, particularly if the difference between the peak and off-peak rates were great. As an example, a recent report regarding peak and off-peak pricing for five electric utilities in California[12] estimated that the off-peak price of electricity would range between 2 and 4 cents per kilowatt-hour, even though the utilities' peak rates varied between 4 and 14 cents per kilowatt-hour. The specific estimates for Pacific Gas and Electric (serving the San Francisco area) were 14.0 cents per kilowatt-hour at the peak rate, and 2.4 cents per kilowatt-hour for the off-peak rate. For averge driving, this would result in an additional $50 per month if on-peak rather than off-peak recharging were used. Not all electric utilities will have this large a differential in peak and off-peak prices. As a result, off-peak pricing may be more effective in some areas of the country than in others.



Source: US Federal Highway Administration, Highway Statistics, 1960-1979 (excludes Alaska and Hawaii)

Figure 6.4 National Motor Fuel Consumption, 1960-1979

6.5 INCENTIVES

The EHV industry is currently in the embryonic stage of development. As a result, it faces stiff competition from the fully-developed conventional automobile industry. Not only are the capital costs required to penetrate the automotive market great, but so are the associated risks. Nevertheless, the potential benefits to the country of an expanded EHV industry are also great. Consequently, the Federal Government has undertaken to play a major role in supporting the development of the EHV industry.

In 1976, the Congress passed the Electric and Hybrid Vehicle Research, Development, and Demonstration (EHV RD&D) Act (Public Law 94-413). Since that time, the Department of Energy has supported an extensive program whose objectives are to improve the capabilities of and expand the market for EHVs. The total budget initially authorized for this program was $160 million through September 1981. Additional funds have been appropriated since that time, particularly in the area of advanced battery research and development. The recent inclusion of EHVs in the calculation of Corporate Average Fuel Economy (CAFE), resulting from an amendment to the Chrysler Corporation Loan Guarantee Act of 1979 (PL 96-185), represents a further Federal effort to encourage their development.

Other means that could be employed to increase the acceptance and use of EHVs include subsidies and tax credits for both producers and purchasers of vehicles, tax credits for electricity used to recharge vehicles, markets for EHVs guaranteed by the Federal Government, and vehicle sharing schemes whereby limited use of a larger conventional vehicle is guaranteed as part of the purchase of an EHV. Possible disincentives for conventional vehicle use, which would improve the relative position of EHVs, would be to increase automotive fuel taxes or vehicle purchase taxes. Gasoline rationing could tend to encourage the purchase of fuel-efficient conventional vehicles rather than EHVs if it is simply used to allocate a limited supply of gasoline without price increases. Rationing accompanied by a "white market" in ration coupons would encourage EHV sales by allowing increases in the effective price of gasoline.

6.5.1 Present Incentives

The stated goal of the EHV R&D program approved by Congress in 1976 is to assure the availability and broad market acceptance of vehicles that depend primarily on externally generated electricity for propulsion energy in order to minimize dependence on imported oil while maintaining continued flexibility in the transportation sector.[13]

The program initially consisted of three major elements: Demonstrations, Incentives, and Research and Development. A fourth major element, Product Engineering, was subsequently added. The purpose of the Demonstration program element is to show that EHVs can perform functions presently accomplished by petroleum-fueled vehicles, to develop the market for EHVs, to develop the support systems necessary to maintain the vehicles in practical operations, and to provide a cash flow to manufacturers. The purpose of the Incentives program element is to remove barriers and facilitate the development and subsequent use of EHVs, primarily through business loan guarantees, small business planning grants, and special studies on barriers to using EHVs. The purpose of the Product Engineering program element is to accelerate the commercialization of EHVs by facilitating the transfer of improved technology into the marketplace, thereby bridging the gap between the Research and Development and the Demonstration elements of the program. The purpose of the Reserch and Development program element is to advance EHV technologies to the point where they are more acceptable, have improved utility, and are available at lower cost. A complete discussion of each of these program elements is presented in the most recent report to Congress on the EHV program.[14]

In order to help achieve the goal of the EHV RD&D program, the following five major projects have been established:

- Market Demonstration. The purpose of this project is to identify, test, and prove EHV market sectors; to develop the necessary support infrastructure; and to provide cash flow to manufacturers.

- Vehicle Evaluation and Improvement. The purpose of this project is to develop improved vehicles through optimization of off-the-shelf technology and to aid the rapid commercial availability of improved vehicles.

- Electric Vehicle Commercialization. The purpose of this project is to induce mass production by 1986 of cost-competitive electric vehicles that will be acceptable to a broad segment of the market.

- Hybrid Vehicle Commercialization. The purpose of this project is to induce mass production by 1988 of cost-competitive hybrid vehicles with a range capability comparable to internal combustion engine vehicles.

- Advanced Vehicle Development. The purpose of this project is to develop by the early 1990s a general-purpose electric or hybrid vehicle system, completely competitive with internal combusion engine vehicles, which does not use any petroleum for operation.

The rationale for these projects is to provide a balance between "market pull" and "technology push," to enhance the demand for EHVs, and to improve their capability simultaneously. Together they represent an attempt to support the newly-developing EHV industry until it becomes self-sufficient.

At present, the industry consists of numerous small companies which are involved in all aspects of EHV design, development, and production, and several large established firms, such as General Motors and General Electric, which are preparing to produce and market EHVs or their associated components. With the probable large-scale entry of the conventional automobile industry into the EHV marketplace, many small companies which were integrally involved in the early development of the EHV industry are attempting to "link up" with these major producers.

Although almost no Federal funding of EHV development was available before 1976, the program has since received additional emphasis each year (Table 6.5). Total funding for FY 1976-1980 was over $130 million, 60 percent of which was allocated for FY 1979 and 1980. The budget emphasis for FY 1980 concentrates on market demonstration projects and research and development, particularly in the area of electric vehicle commercialization. Nearly 70 percent of the present budget is directed at these two major efforts.

Since batteries are one of the major cost components of EHVs, and since they are the limiting factor in EHV range, significant additional funding has been allocated to improve technology in this area. The Department of Energy supported advanced battery research and development even before the EHV RD&D Act of 1976. However, the level of effort has been increased since that time such that FY 1980 funding is $41 million (Table 6.6). Although the zinc-chlorine, lithium-aluminum metal sulfide, and sodium-sulfur battery programs are currently receiving the greatest emphasis, other batteries which also show some promise are being funded, but to a lesser extent. Increased funding for the most promising battery R&D projects will most likely be required to achieve the technological advances necessary to make EHVs cost-competitive and to provide sufficient range.

Another recent incentive for EV production by the major automobile manufacturers is the inclusion of EVs in the computation of Corporate Average Fuel Economy (CAFE). This incentive was initiated as a result of an amendment to the Chrysler Corporation Loan Guarantee Act of 1979 (PL 96-185). EV fuel economies as high as 185 miles per gallon have been proposed for use in the CAFE computation.[15] Even at much lower fuel EV economy estimates, the differential between fuel economy for conventional vehicles and EVs appear large enough to provide a significant improvement in CAFE if sufficient EVs are manufactured and sold. Market demand for fuel efficient automobiles is already such, however, that the major manufacturers are expected to exceed the current standards through 1985. In this case, EVs are not needed to meet the standards.

TABLE 6.5

DOE EHV PROGRAM AND PROJECT FUNDING

Programs	FY 1976-1978, millions of dollars	FY 1979, millions of dollars
Demonstrations	5.5	12.1
Incentives	0.9	2.5
Product Engineering[1]	10.9	6.9
Research and Development	35.5	16.0
	52.8	37.5

Projects	FY 1980, millions of dollars
Market Demonstration	12.0
Vehicle Evaluation and Improvement	2.5
Electric Vehicle Commercialization	17.0
Hybrid Vehicle Commercialization	7.5
Advanced Vehicle Development	3.5
	42.5

Source: 3rd Annual Report to Congress for FY 1979, Electric and Hybrid Program, US Department of Energy, January 1980; and Mort Cohen, Aerospace Corporation, Washington, D.C., private communication, June 1980.

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[1] Includes near-term battery development and technology demonstrations.

TABLE 6.6

DOE BATTERY R&D FUNDING

Battery System	Millions of Dollars FY 1975	Millions of Dollars FY 1980
Improved Lead-Acid	2.3	2.7
Nickel-Iron	0.5	1.5
Nickel-Zinc	1.3	2.3
Metal-Air	2.2	1.7
Zinc-Chlorine	0.5	4.1
Lithium-Aluminum Metal Sulfide	5.0	6.5
Sodium-Sulfur	3.2	6.0
	15.0	24.8[1]

Source: F. George, Electromechanical Power Sources for Electric Highway Vehicles, Arthur D. Little, Inc. Report C-74692, June 1972; N. P. Yao, Argonne National Laboratory, private communication; and Kurt Klunder, US Department of Energy, private communication.

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[1] The total budget for advanced battery research and development is $41 million. The additional $16.2 million is to be used for test facilities, special studies, support, and exploratory work on other batteries.

6.5.2 Possible Future Incentives

Various incentives that could be implemented to stimulate the transition from conventional vehicles to EHVs are described below.

Subsidies and Tax Credits. These are the most common general incentives that have been used by the Federal Government to stimulate new technology. They are primarily used to offset the economic disadvantages of a particular technology when the overall benefits to the nation can be better served. However, they do interfere with the normal workings of the marketplace. Consequently, special care must be taken to ensure that the resulting benefits warrant this interference.

Direct subsidies to vehicle manufacturers and buyers could be used to encourage EHV production and purchase. A recent study by SRI International estimated that it could cost $7 to $12 billion by the year 2000 to equalize the initial purchase prices of conventional and electric vehicles.[7] This is based on an expected fleet size of 3.5 million electric vehicles with subsidies of $2000 to $3500 each. Tax credits for producers and purchasers could provide an incentive similar to those of subsidies, without extensive cash outlays by the government, but they would result in foregone tax revenues. A similar tax credit could also be applied to recharge electricity usage to reduce further the overall life-cycle costs of EHVs. The potential impacts of these measures have not yet been studied in detail.

Market Guarantees. Because of uncertainties in the marketplace regarding consumer acceptance of EHVs, manufacturers must be careful in initiating an extensive campaign to produce and market these types of vehicles. However, most experts feel that at least 20 percent of the light-duty vehicle market must be captured by 2010 in order to justify the cost of government incentives. In order to help provide a sound market, and to demonstrate government confidence in the utility of EHVs, it may be advantageous to guarantee the purchase of EHVs for government use. The Federal Government currently utilizes many conventional vehicles which could adequately be replaced by EHVs. However, this would involve at most only about one million passenger vehicles, and would represent less than six-tenths of one percent of the projected light-duty vehicle population in 1985.

Automotive Fuel Taxes. The appeal and marketability of EHVs might also be increased through the use of a disincentive such as higher gasoline taxes to discourage gasoline consumption. These taxes would make EHVs more attractive by reducing operating costs in comparison to conventional vehicles. However, they would result in various side effects which could require compensatory action by the Federal Government.

Fuel Rationing. A measure closely related to higher fuel taxes is fuel rationing. Recent Administration and Congressional actions have formulated a stand-by gasoline rationing plan as a means of decreasing consumption if the foreign oil import situation becomes critical. Although rationing is generally considered a "last resort" response, the prospect of imposition could affect EHV purchases. During World War II, rationing stabilized the price of gasoline while reducing consumption; i.e., pump prices were fixed, available quantities of gasoline were reduced, and consumers were provided with non-transferable coupons. If this type of rationing were again implemented, it would not provide an advantage to EHV owners because the price of electricity would continue to rise, thus reducing the price differential between it and the stabilized gasoline price. In this case, consumers would be better off to purchase an inexpensive, fuel-efficient conventional automobile which would not have the range restrictions of an electric. Only if rationing were to result in a net increase in the effective price of gasoline, thus increasing the differential between gasoline and electricity, would it provide an incentive to purchase an EHV. In this case, coupons would be transferable, resulting in an effective gasoline price consisting of the cost of the gasoline itself and the cost of a coupon. These coupons would be purchased from individuals who chose to sell them rather than consume their allocated share of gasoline. As rationing became more and more stringent, a larger number of consumers would enter the market to purchase coupons, further increasing prices. The net effect would be similar to increased levels of gasoline taxation.

Vehicle-Sharing Schemes. Various vehicle-sharing schemes have been considered in recent years to help eliminate the disadvantages of electric vehicles with regard to long-distance travel. For example, electric vehicle dealers could guarantee buyers limited use of a larger conventional vehicle as part of the purchase agreement. These conventional vehicles could be owned by the dealers and be provided to purchasers of electric vehicles by appointment to use for vacations, weekend trips, transporting large loads, etc. It is not clear exactly how these schemes could best be employed, or whether they would remain desirable if hybrids enter the marketplace.

A study performed by Mathtech[16] in 1977 examined the effects of a variety of EHV incentives. The study first defined a base case without incentives, and then measured the result of each potential incentive in relation to this base case (Table 6.7). The study estimated that less than 40,000 electric vehicles would be sold in 1995 without the use of incentives. Purchase price subsidies showed the greatest promise: a $3000 subsidy per vehicle was projected to boost estimated sales to over 850,000 in 1995. An operating subsidy of one-third of most life-cycle costs also showed great promise, boosting sales over the 450,000 mark. Although a gasoline tax of 50 cents per gallon could also increase EV sales, it would not be as effective as either of the first two incentives. The study found that the use of multiple incentives would provide the greatest increase in EHV purchases. In the case of a 50-cent per gallon gasoline tax and a one-third operating subsidy, electric vehicle sales in 1995 were projected to exceed 1,200,000.

Another study of incentives was performed by Arthur D. Little, Incorporated.[8] The study projected sales of various types of vehicles for 1983, including both electric and hybrid vehicles (Table 6.8). The study estimated that from two to seven times as many hybrids as electrics would be sold in 1983, depending upon the incentives used. The use of a $2000 subsidy and a special warranty was projected to result in sales of over 800,000 in 1983.

Current estimates by General Motors are on the order of 200,000 to 300,000 EHVs per year by the late 1980s, presumably with no incentives. These estimates differ substantially from the base cases for the Mathtech and A. D. Little studies.

TABLE 6.7

PROJECTION OF ANNUAL ELECTRIC VEHICLE SALES UNDER ALTERNATIVE POLICIES

	1985		1995	
Incentives	Number	Percent Increase	Number	Percent Increase
Base Case (no incentives)	20,300	--	36,900	--
$300 Purchase Subsidy	38,000	38	50,900	38
$1000 Purchase Subsidy	59,600	194	107,400	191
$3000 Purchase Subsidy	503,000	2378	867,800	2252
Off-Peak Electricity Pricing	27,100	33	49,900	35
50-cent Gas Tax	51,900	156	102,400	178
10-cent Gas Tax	25,300	25	45,500	23
Doubling of Range	55,900	175	114,200	209
Operating Subsidy of one-third of most life-cycle costs	240,100	108	465,500	1161
Combination of 50-cent Gas Tax and Doubling of Range	144,800	613	313,400	749
Combination of 50-cent Gas Tax and Operating Subsidy	601,700	2860	1,221,100	3209

Source: C. Upton and C. Agnew, An Analysis of Federal Incentives to Stimulate Consumer Acceptance of Electric Vehicles, Mathtech, September 1977.

TABLE 6.8

ESTIMATED SALES OF EHVs TO CONSUMERS IN 1983[1]

Incentive[2]	Vehicle Sales, thousands Electric	Hybrid
Base Case (no incentives)	37	984
Special Warranty	73	514
Subsidy of $2000[3]	257	440
Subsidy and Warranty	477	807

Source: Anton S. Morton, Incentives and Acceptance of Electric, Hybrid and Other Alternative Vehicles, Arthur D. Little, Inc., November 1978.

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[1] Assumes total new car sales of 10 million. Estimates total of 3.7 million sold to potential market for EHVs (multiple-car households which own at least one compact or subcompact car and live in warm or temperate climates.

[2] Gasoline at $1 per gallon.

[3] 1978 dollars

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7 BENEFITS AND COSTS, MONETARY AND NON-MONETARY

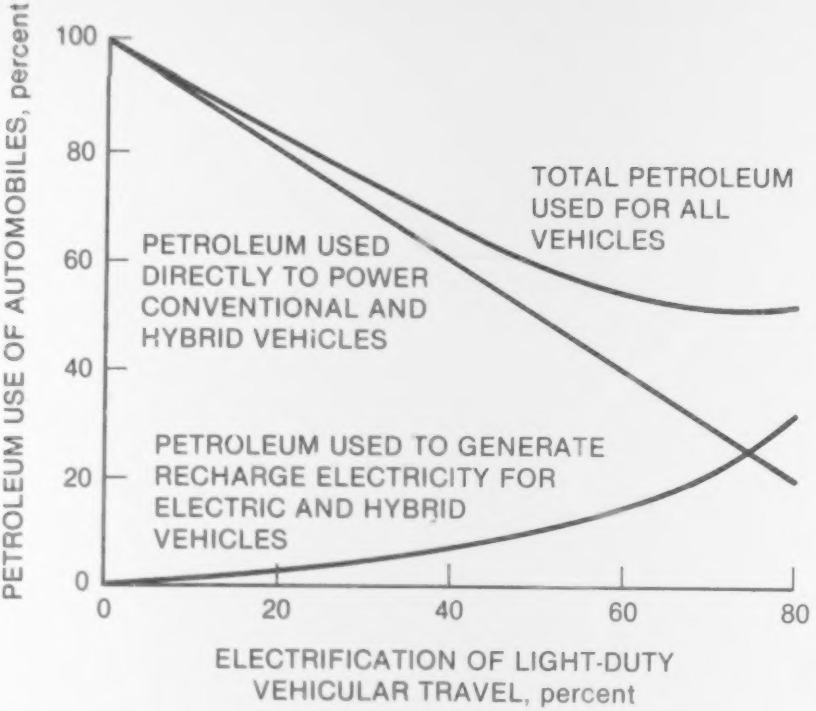
7.1 SUMMARY

No one knows with any degree of certainty how many EHVs will be sold in the 1985-2010 time frame. It is clear, however, that EHVs can provide various benefits to the nation and the user, given a willingness to accept the associated costs. Though any attempt to estimate benefits and costs must rely on an arbitrary assumption of EHV sales, it is clear that at any sales level, EHVs can save petroleum. It is also clear that EHVs initially will be more expensive than comparable conventional vehicles, and that electric vehicles will provide the user with substantially less mobility.

The benefits and costs of EHVs can generally be divided into five major categories: energy, the environment, the economy, resources, and transportation. In terms of energy, the primary benefits of using EHVs would be a reduction of petroleum consumption and a lessening of US dependence on foreign oil. For example, in the year 2010, electrification of 20 percent of light-duty vehicle travel would reduce automotive petroleum consumption by nearly 18 percent (Fig. 7.1). Furthermore, if EHVs were utilized first in selected regions, up to 70 percent of all light-duty vehicular travel could be electrified without using any petroleum to generate recharge electricity. This would result in automotive petroleum savings of about 65 percent. In this case, most of the electricity would be derived from coal and nuclear power plants during otherwise idle off-peak periods. With market penetrations of less than 20 percent, savings would be proportionately smaller.

The primary environmental impacts from the use of EHVs would be an improvement in national air quality and a reduction in urban traffic noise. Since EHVs do not produce emissions like conventional internal combustion engines (when operating in the electric mode), the contribution of automobiles to air pollution would be reduced. However, the generation of recharge electricity through the use of fossil fuels would result in increased sulfur-oxide emissions which would partially offset this improvement. To mitigate this problem, the use of EHVs could be encouraged in those areas where electric generation is least dependent on fossil fuels. Because they are inherently quieter than conventional vehicles, the use of EHVs could also be expected to result in desirable reductions in traffic noise, the major noise problem in urban areas.

The higher prices of EHVs would substantially impact motorists. Aside from this, however, the widespread use of EHVs would have little economic impact in the United States. Only about 3 percent of US jobs would be affected by a complete switch to EHVs. Even if such a transition were completed in only two or three decades, the annual changes would be very small. Total employment in manufacturing, selling, and servicing automobiles would be increased. The overall net change in



Source: Recharge Capacity Projection System (RECAPS), General Research Corporation

Assumptions: The RECAPS model schedules the use of nuclear, coal, and hydroelectric facilities before oil and gas facilities, and base-load facilities before intermediate and peaking facilities to minimize operating costs. Recharging is controlled to maximize the use of off-peak power available during late night and early morning hours whern demand is lowest. The model makes use of capacity and demand projections developed by the electric utility companies in 1979. Energy required was assumed to be 0.5 kilowatt-hours per mile at the charging outlet This value reflects a mix of cars and light-duty trucks to electrify 20 percent of light-duty vehicular travel in 1980, 1990, 2000, and 2010 (Table 6.1). Vehicles were assumed to be distributed uniformly across the Unlited States based on population. They were also assumed to travel an average of 10,000 miles per year. Electrical distribution system efficiency was assumed to be 90 percent.

Figure 7.1 Petroleum Use with Electric and Hybrid Vehicles in 2010

employment and payrolls would be insignificant, amounting to about a one-percent increase even in the extreme case of a complete shift to EHVs. Though some battery materials might be imported, their costs would be offset by savings on imported petroleum.

The widespread use of EHVs would considerably increase the demand for materials used in batteries. However, electrifying 20 percent of the personal cars in the United States by 2010 would probably create no serious shortages of materials. In the absence of interruptions of imports, the increase in the demand for battery materials caused by the production of EHVs is unlikely to precipitate price increases for these materials in the long run, except for lithium, cobalt, and nickel. Even then, increases are not expected to exceed 20 percent if suppliers are given sufficient lead time (perhaps ten years) to plan an orderly expansion of exploration activities and production facilities. Although the identified reserves of battery materials are no more abundant than those of petroleum for meeting world demand through 2010, new discoveries are likely to increase the identified reserves of battery materials as demand increases. Uncertainties are greatest for lithium, partly because it may also be in great demand for use in fusion power plants. However, alternative future batteries based on such abundant materials as sodium, sulfur, and chlorine could effectively eliminate problems of inadequate resources.

Owners of EHVs would have the advantage of a vehicle which does not depend on petroleum as a primary fuel. They would also have the convenience of at-home recharging. Their vehicles would operate more quietly and might be more reliable and maintainable than conventional vehicles. The primary disadvantage to the hybrid vehicle owner primarily would be higher purchase price, particularly in the near term. Overall life-cycle costs (at 1980 gasoline and electricity prices) would be higher in the near term, but might become 8 to 11 percent lower than those of conventional vehicles if advanced EHVs become available. Owners of electric vehicles would not only pay more, but would also be limited to ranges of less than 100-150 miles between recharges.

There are major uncertainties surrounding the future of EHVs. They include the extent to which expected improvements in battery technology can be realized, the actual level of market penetration that EHVs can achieve, the future growth and utilization of the electric utility industry, and the extent to which improvements in conventional vehicles reduce the potential advantages of EHVs.

7.2 ENERGY

The use of EHVs to electrify 20 percent of light-duty vehicular travel would result in a significant reduction in petroleum consumption. In the year 2010, automobile petroleum use would be cut by 16 to 20 percent, saving approximately 600,000 barrels of crude oil per day, or 4 percent of projected future national petroleum consumption. Even greater petroleum savings could be achieved if EHVs were selectively implemented in those regions which would use little or no petroleum to generate recharge energy. However, the national use of coal and nuclear fuels would be increased correspondingly as electric utilities generated recharge electricity during otherwise idle off-peak periods.

The fuel economy of future conventional vehicles and the fleet size determine vehicular petroleum consumption without EHVs. Fuel economy assumptions used in this report for passenger and light trucks range from 14.3 miles per gallon in 1980 to about 40 miles per gallon in 2010 (Table 7.1). Based on these assumptions, energy required from petroleum used directly as fuel in conventional automobiles would be approximately 14 quadrillion BTUS (quads) in 1980, 10 quads in 1990, 7.5 quads in 2000, and 6 quads in 2010 (equivalent to 6.6, 4.7, 3.5, and 2.8 million barrels of oil per day). As these figures show, increases in fuel economy in the 1980-2010 time frame might reduce petroleum consumption of automobiles by more than 50 percent, even without the use of EHVs.

Based on the expected electricity and gasoline use for electric, hybrid, and comparably-constructed conventional cars, it is possible to determine the equivalent fuel economies for the simple case where all energy for vehicle operation is derived from either petroleum or coal (Table 7.2). In the case of petroleum, near-term electric and hybrid cars would provide from 6 to 20 percent less fuel economy than comparable conventional cars. However, advanced electrics and hybrids would provide a 4 to 18 percent improvement over conventional cars. In other words, if petroleum were the sole fuel used to power automobiles, only the advanced electric and hybrid cars would be more fuel-efficient than conventional vehicles, an advantage that could be eliminated if ICE vehicles attain fuel economy higher than assumed here.

In the case of coal, the equivalent fuel economies of electric and hybrid cars are quite high, largely because of the inefficiency of synthesizing gasoline from coal. In fact, both near-term and advanced EHVs would be more fuel-efficient than the assumed conventional vehicles. Near-term electrics and hybrids would provide the equivalent of a 33 to 75 percent increase in fuel economy, and advanced vehicles would provide an 80 to 105 percent advantage.

In practice, of course, neither coal nor oil alone would be used as energy sources for EHVs. Instead, electric utilities would use those fuels and facilities which are most cost-effective and available. In general, most recharge energy would come from a mix of coal, nuclear, and petroleum fuels which would vary from utility to utility, and from hour to hour during the day. If recharging occurred during otherwise idle, off-peak hours in 2010, for example, the use of oil in generating recharge electricity would drop to about 7 percent and coal would become

TABLE 7.1

FUEL ECONOMY OF FUTURE CARS AND LIGHT TRUCKS

Year	Assumed New Car Composite Fuel Economy, mpg	New Vehicle Urban Fuel Economy, mpg		Fleet Fuel Economy, mpg		Fleet Fuel Economy For Cars and Light Trucks, mpg
		Cars	Light Trucks	Cars	Light Trucks	
1980	21	18.3	13.9	14.8	12.6	14.3
1990	34	29.6	21.8	24.3	18.1	22.7
2000	45	39.2	26.1	35.0	22.3	31.2
2010	55	47.9	32.0	44.0	28.2	39.9

Source: General Research Corporation

Derivation: Assumptions were first made of new-car composite fuel economy for 1980-2000. These assumptions were based on the premise that new vehicles exceed CAFE standards in 1980 and will meet them in 1985. After 1985, composite fuel economy will improve at the rate of about 1 mpg per year. Urban new-car fuel economy was then derived by taking 87 percent of each composite mpg. Trucks were assumed to consume 50 percent more fuel than cars because of larger loads. Actual in-use fuel economy was assumed to be equal to urban fuel economy. Fleet averages assume a mix of old vehicles and new vehicles, thus resulting in fleet averages which are below the new-vehicle fuel economies. Assumed fleet sizes are given in Table 6.1.

TABLE 7.2

SUMMARY OF FUEL USE AND EQUIVALENT FUEL ECONOMY OF ELECTRIC, HYBRID, AND CONVENTIONAL FOUR-PASSENGER SUBCOMPACT CARS

	Basic Fuel Use		Equivalent Fuel Economy Resource Utilization, mpg[1]	
Vehicle	Electricity, kWh per mile	Gasoline, mpg	Oil	Coal
Electric				
Near-Term:				
Pb-acid	0.40	--	29.0	50.0
Ni-Fe	0.44	--	26.0	45.0
Ni-Zn	0.38	--	30.0	53.0
$Zn-Cl_2$	0.45	--	26.0	44.0
Advanced:				
$Zn-Cl_2$	0.31	--	37.0	64.0
Li-MS	0.30	--	38.0	67.0
Hybrid				
Near-Term:				
Pb-acid	0.38	31.0	31.0	53.0
Ni-Zn	0.37	34.0	33.0	58.0
Advanced:				
Li-MS	0.27	45.0	42.0	73.0
Conventional (ICE)[2]				
Near-Term	--	33.0	33.0	33.0
Advanced	--	35.6	35.6	35.6

Source: Tables 3.5, 3.7, 4.1, and 4.4 of this report.

Assumptions: See assumptions for each table listed above.

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[1] Urban fuel economies are presented which are about 87 percent of composite fuel economy.

[2] Assumes that conventional vehicles are comparable to EHVs, i.e., same basic construction techniques and materials are used in all vehicles, with engine efficiencies of the 1980's.

the dominant fuel, providing nearly 65 percent of all recharge energy. Nuclear power would be used to satisfy approximately 25 percent of the load (Fig. 7.2).

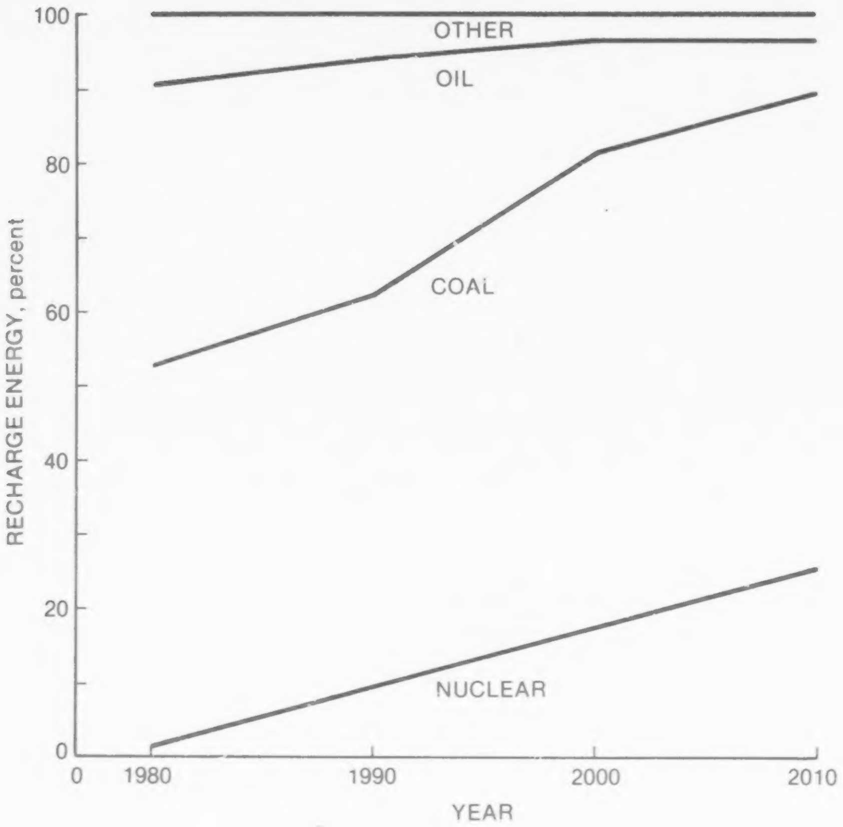
The fact that electrics do not use gasoline, hybrids use little gasoline, and electric recharge energy could be generated using little petroleum, provides the basis for estimating reduced petroleum consumption through the use of EHVs. If EHVs were used uniformly throughout the United States to electrify 20 percent of light-duty vehicular travel, petroleum used for automobiles would be reduced by 14 to 18 percent over the 1980-2010 time frame (Fig. 7.3).[1] However, if EHVs were selectively encouraged in those areas of the country where little or no petroleum would be required to generate recharge energy, a savings of up to 20 percent would result. The Mid-Atlantic, East Central, Southeast, Mid-America, and Mid-Continent regions would be best, but the Southwest and Texas regions also show some potential. The Northeast and West regions, due to their dominant use of oil-fired power plants, would be much less suitable on the whole. However, even in these areas, careful analysis of the particular fuel mixes used to generate power for selected cities could identify some with potential for saving petroleum. Other considerations such as air quality, terrain, weather, etc., would also enter into the selection of suitable areas for EHV use.

It would be possible to save even more petroleum if EHV market penetration were higher. At 80-percent electrification of light-duty vehicular travel, petroleum use by automobiles could be reduced by more than 70 percent in the year 2010. If EHVs were first utilized in selected regions, up to 60 percent of light-duty vehicular travel could be electrified with virtually no use of petroleum for generating recharge energy by the year 2000, and up to 70 percent by the year 2010.

The impacts of 20-percent electrification of light-duty vehicular travel on overall national energy use would also be significant (Table 7.3): a reduction of 3.8 percent in 1990 or 2000 and 4.2 percent in 2010. Though these percentages are small, they represent significant absolute savings of petroleum, on 660,000 to 520,000 barrels per day. Although overall national energy use would increase between 1980 and 2010, and oil consumption would be reduced in the absence of EVHs because of other actions, EHV use would result in an even greater shift from petroleum to other sources of energy.

7.3 ENVIRONMENT

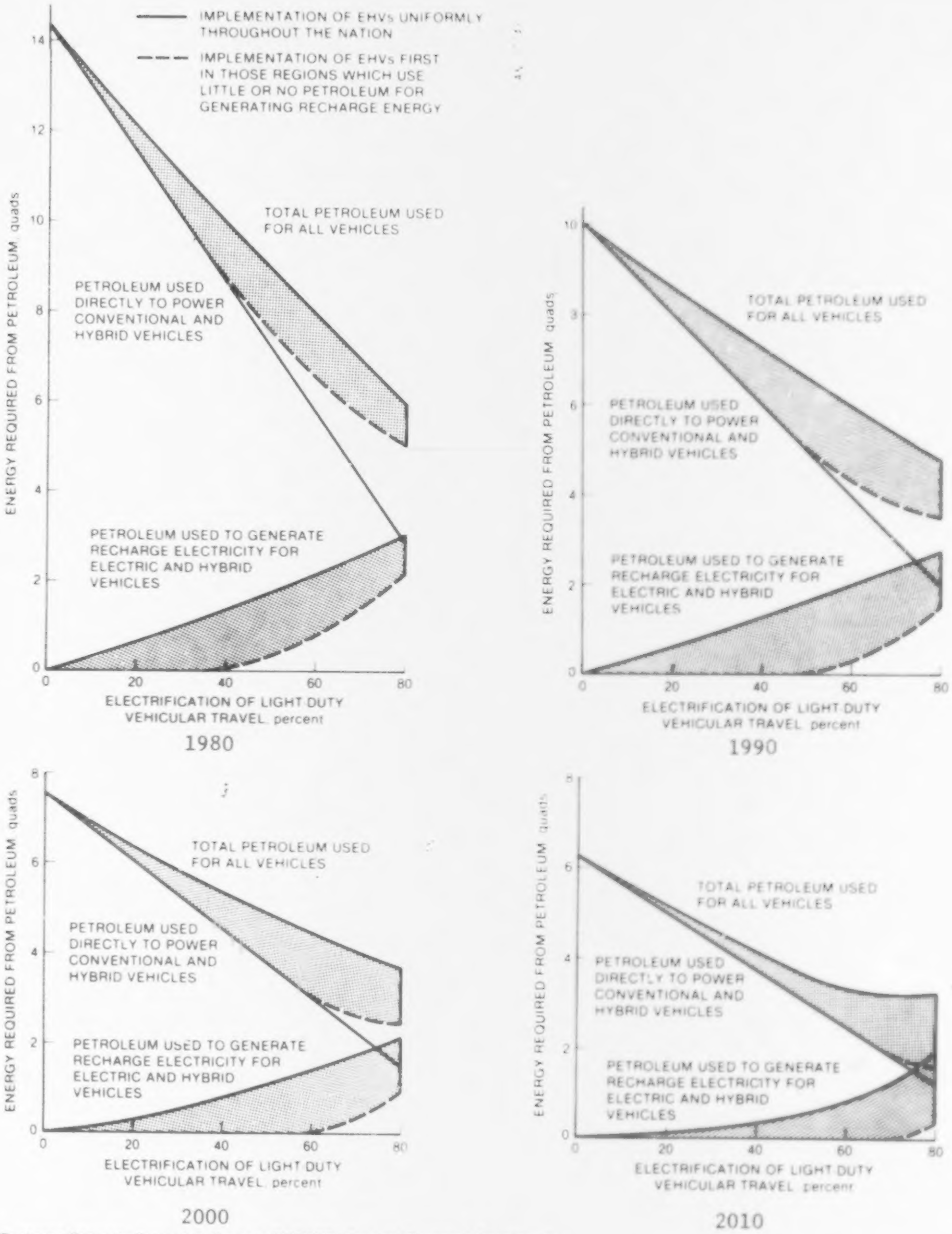
There would be little change in air pollution associated with 20-percent electrification of light-duty vehicular travel. Although the use of EHVs would result in a reduction in the amount of automobile emissions, there would be an increase in power plant emissions. The net effect would be only a slight improvement in overall national air quality. However, there would be larger regional variations that would



Source: Recharge Capacity Projection System (RECAPS), General Research Corporation

Assumptions: The RECAPS model schedules the use of nuclear, coal, and hydroelectric facilities before oil and gas facilities, and base-load facilities before intermediate and peaking facilities to minimize operating costs. Recharging is controlled to maximize the use of off-peak power available during late night and early morning hours whern demand is lowest. The model makes use of capacity and demand projections developed by the electric utility companies in 1979. Energy required was assumed to be 0.5 kilowatt-hours per mile at the charging outlet This value reflects a mix of cars and light-duty trucks to electrify 20 percent of light-duty vehicular travel in 1980, 1990, 2000, and 2010 (Table 6.1). Vehicles were assumed to be distributed uniformly across the Unlited States based on population. They were also assumed to travel an average of 10,000 miles per year. Electrical distribution system efficiency was assumed to be 90 percent.

Figure 7.2 Projected Use of Fuel for 20 Percent Electrification of Light-Duty Vehicular Travel



1980

1990

2000

2010

Source: Recharge Capacity Projection System (RECAPS), General Research Corporation

Assumptions: The RECAPS model schedules the use of nuclear, coal, and hydroelectric facilities before oil and gas facilities, and base-load facilities before intermediate and peaking facilities to minimize operating costs. Recharging is controlled to maximize the use of off-peak power available during late night and early morning hours whern demand is lowest. The model makes use of capacity and demand projections developed by the electric utility companies in 1979. Energy required was assumed to be 0.5 kilowatt-hours per mile at the charging outlet. This value reflects a mix of cars and light-duty trucks to electrify 20 percent of light-duty vehicular travel in 1980, 1990, 2000, and 2010 (Table 6.1). Vehicles were assumed to be distributed uniformly across the Unlited States based on population. They were also assumed to travel an average of 10,000 miles per year. Electrical distribution system efficiency was assumed to be 90 percent. The results have been adjusted to account for power plant efficiency of 35 percent, refinery efficiency of 93 percent, and ancillary energy for oil recovery and transport of 3.4 percent.

Figure 7.3 Petroleum Use by Electric, Hybrid, and Conventional Vehicles

TABLE 7.3

NATIONAL USE OF ENERGY WITHOUT AND WITH 20 PERCENT ELECTRIFICATION OF LIGHT-DUTY VEHICULAR TRAVEL, QUADRILLION BRITISH THERMAL UNITS PER YEAR

	1990			2000			2010		
	Without	With	Percent Change	Without	With	Percent Change	Without	With	Percent Change
Nuclear	11	11.17	+ 1.6	17	17.35	+ 2.0	22	22.52	+ 2.4
Coal	28	29.01	+ 3.6	39	40.24	+ 3.2	49	50.30	+ 2.7
Oil	37	35.60	- 3.8	32	30.79	- 3.8	26	24.90	- 4.2
Other	26	26.11	+ 0.4	29	29.07	+ 0.3	32	32.07	+ 0.2
	102	101.89	- 0.1	117	117.45	+ 0.4	129	129.79	+ 0.6

Sources: The President's National Energy Plan, Vol. 1, 1979; and the Recharge Capacity Projection System (RECAPS), General Research Corporation

Assumptions: Total energy use projections without EHVs were derived from the President's National Energy Plan II, submitted to Congress in the spring of 1979. These projections were selected because they assume "medium world oil prices" in 1980, and then a subsequent transition to "high world oil prices" by 2000, continuing to 2010. They also assume that various transitional and ultimate energy technologies will be developed, such as the use of direct petroleum substitutes, e.g., heavy oils, tar sands, synthetic liquids, and solar power.

provide an opportunity to encourage the use of EHVs selectively where they could have the greatest positive effect on air quality. The level of expected improvement in air quality would decline somewhat between 1980 and 2010 as conventional vehicles become cleaner, thus limiting the extent to which EHVs could improve future air quality.

Other environmental effects of EHV use are reduced urban traffic noise, effects on public health and safety (resulting primarily from the increased use of coal-fired and nuclear power plants), thermal pollution from power plants, and reduced dumping of waste crankcase oil. The use of EHVs would reduce the urban traffic noise problem because these vehicles are inherently quieter to operate than conventional vehicles, particularly when compared to those with small, high-speed ICE engines or diesels. The other areas of concern would be little affected by 20-percent electrification of light-duty vehicular travel, but are mentioned here because they have been of recent public concern. Though their importance is difficult to estimate, especially in the case of risks from nuclear reactors, fuels, and wastes, all appear to be relatively minor considerations in relation to EHVs.

7.3.1 Air Quality

The amount of pollution produced by automobiles and electric utilities would change as a result of the widespread use of EHVs. Since EHVs do not emit pollutants when operating in the electric mode, except for small amounts of particulates due to tire wear, automobile emissions would be reduced in proportion to EHV miles driven. Power plant emissions, on the other hand, would increase to the extent that fossil fuels were used to generate the additional electricity needed for recharging. Analysis of the projected contributions of conventional automobiles and power plants to emissions between 1980 and 2010, in the absence of EHVs, shows the effect of the Clean Air Act of 1970 and its amendments (Table 7.4). Percent contributions of both automobiles and power plants are dropping. If the scheduled regulations are implemented and met in time, nearly 90 percent of all automobile emissions will be eliminated by 1985. Additional Clean Air Act requirements will also result in improved control of power plant emissions. These tend to limit the extent to which EHVs can improve overall national air quality, no matter how many are used to replace conventional vehicles. However, even at 20-percent electrification of light-duty vehicular travel, sufficient regional variation exists to warrant consideration of selectively encouraging EHV use in those areas where the greatest benefit could be achieved.

The regional variation in air quality resulting from the use of EHVs depends on the location of the power plants that serve the region, the fuels used to generate recharge electricity, the vehicle miles driven in electric mode, and to some extent, the characteristics of the region, including local emission regulations and vehicle mixes. For example, the population-weighted average of composite pollution indicators for the 24 largest air-quality control regions (AQCRs) in the

TABLE 7.4

PERCENT CONTRIBUTION OF AUTOS AND POWER PLANTS TO EMISSIONS

WITHOUT EHVs

	Contribution of Vehicles, percent				Contribution of Power Plants, percent			
Pollutant	1980	1990	2000	2010	1980	1990	2000	2010
Total Suspended Particulates	10	9	9	9	10	7	6	5
Sulfur Oxides	0	0	0	0	38	32	26	20
Nitrogen Oxides	20	14	14	14	23	21	20	19
Total Hydrocarbons	25	13	12	11	0	0	0	0
Carbon Monoxide	54	38	38	38	0	0	1	2

Source: Regional Emissions Projection System (REPS). General Research Corporation

Assumptions: Industrial growth projections were for 1977, and were obtained from the Department of Commerce OBERS model. Base year emissions data were for 1975, and were obtained from the National Emission Data System (NEDS). Electric utility growth projections were based on the Recharge Capacity Projection System (RECAPS) output generated both with and without EHV use. Emissions from facilities built after 1978 were assumed to be controlled to the level required by the new source performance standards proposed in or before 1978. Emissions from facilities built prior to 1978 were assumed to be controlled to the level defined in NEDS. These projections, therefore, do not fully reflect the effect of the 1977 Amendments to the Clean Air Act which require that states submit revised State Implementation Plans (SIPS) which assure that future air quality will satisfy the national primary standard. Analysis was based on the 24 most populated air quality control regions (AQCRs) in the United States. The results reflect population-weighted averages.

United States in 2000, given 20-percent electrification of light-duty vehicular travel, shows a 2.4 percent improvement (Table 7.5). However, two AQCRs--San Francisco and San Diego--would experience more than a 5-percent improvement in air quality, and another eight--Boston, Seattle, Denver, Los Angeles, Miami, Washington, D.C., Buffalo, and Dallas--would experience an improvement of more than 3 percent. On the other end of the spectrum, overall air quality would decrease if EHVs were used in Pittsburgh. This is because those power plants required to generate recharge energy are primarily located in the urban area itself. Furthermore, these plants are primarily coal-fired, thus increasing the urban sulfur-dioxide problem.[2]

To set the impact of EHVs on air quality in perspective, it is first necessary to understand the expected trends of future air quality in the absence of EHVs (Fig. 7.4). In general, the main air pollution problems through the year 2010 are projected to be total hydrocarbons and total suspended particulates, which will increase 35 and 16 percent, respectively. Both are now, and will continue to be, significantly above the 1975 standard. On the other hand, new federal standards proposed in 1978 for sulfur oxides, nitrogen oxides, and carbon monoxide can be expected to control these pollutants. Although sulfur oxides and nitrogen oxides will increase 6 percent and 14 percent, respectively, they will continue to be below the standard. Carbon monoxide will be reduced by 44 percent, but will still be slightly above the standard. All these projections are based on 1978 state implementation plans (SIPs), and will change as these plans are updated and new regulations are promulgated.

The national impact on air quality of 20-percent electrification of light-duty vehicular travel will result in a rise in sulfur oxides and decreases in nitrogen oxides, total hydrocarbons, and carbon monoxide (Fig. 7.5). Total suspended particulates will be little affected. Sulfur oxides in 1980 would be increased by about 3.5 percent, but would decrease to less than one percent above the 2010 level over the next 30 years. Nitrogen oxides would be reduced by 1 to 2 percent over the 1980-2010 time frame. Total hydrocarbons would be reduced by 5 percent in 1980, but would be about 2 percent under expected baseline levels in 2010. Carbon monoxide initially would drop by 10 percent in 1980, but would stabilize at over 6 percent in 2010. This general trend of significant initial impact, tapering off to modest levels by 2010, is primarily due to the fact that federal standards for both conventional automobiles and power plants will tend to reduce the potential effect of EHVs on national air quality.[2]

7.3.2 Urban Traffic Noise

The importance of noise pollution and its control have been recognized in recent years in legislation at all levels of government. In particular, the Federal Noise Control Act of 1973 established as a national policy the control of emissions of noise that are detrimental

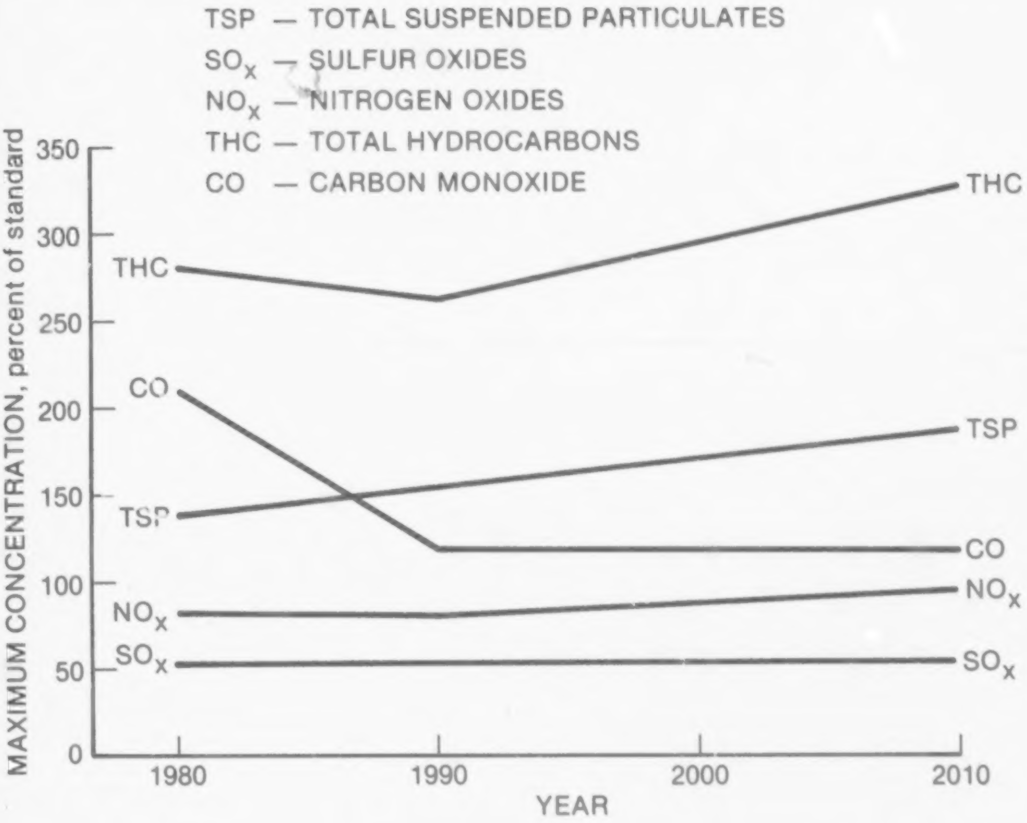
TABLE 7.5

CHANGE IN THE SEAS COMPOSITE POLLUTION INDICATOR WITH 20 PERCENT ELECTRIFICATION OF LIGHT-DUTY VEHICULAR TRAVEL

Air Quality Control Region	Decrease in Pollution Indicator Resulting from Use of EHVs, percent 2000
San Francisco	5.5
San Diego	5.4
Boston	4.1
Seattle	3.8
Denver	3.5
Los Angeles	3.4
Miami	3.4
Washington, D.C.	3.2
Buffalo	3.1
Dallas	3.0
New York	2.7
Atlanta	2.5
Detroit	2.3
St. Louis	1.9
Philadelphia	1.8
Minneapolis-St. Paul	1.8
Baltimore	1.7
Chicago	1.6
Cleveland	1.6
Milwaukee	1.6
Kansas City	1.5
Houston	1.2
Cincinnati	0.9
Pittsburgh	-1.6
Population-Weighted Average	2.4

Source: Regional Emission Projection System (REPS), General Research Corporation; and Strategic Environmental Assessment System (SEAS), originally developed by several private corporations for EPA and now under the control of the Environment Division of DOE.

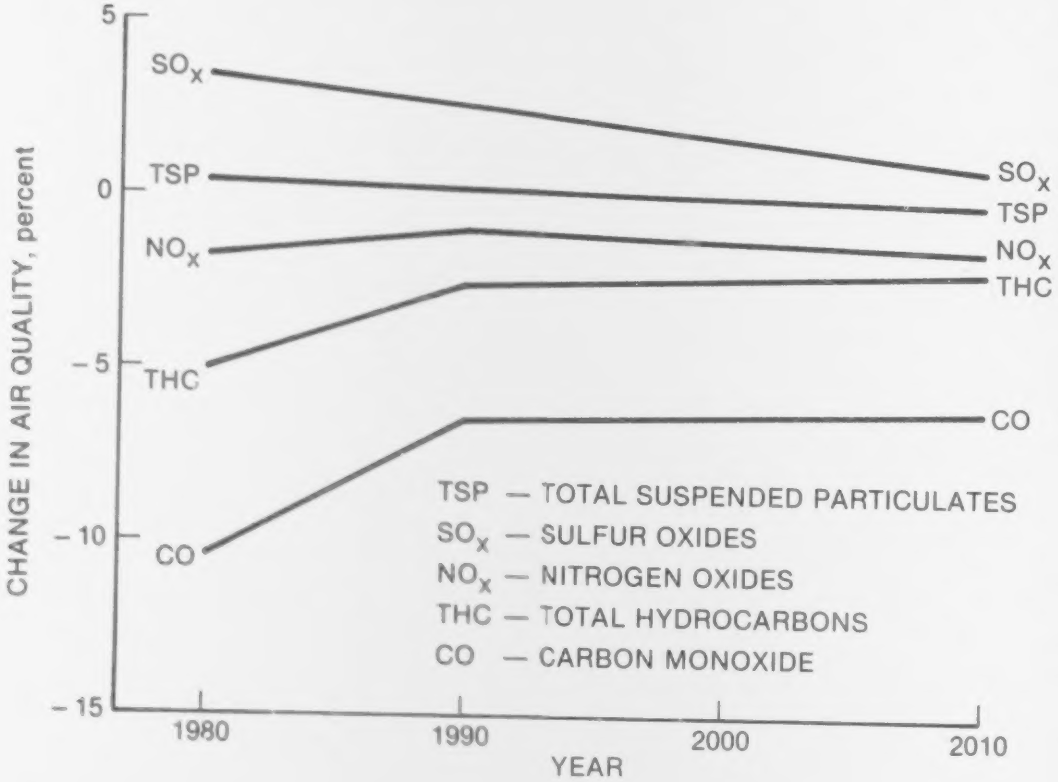
Assumptions: Industrial growth projections were for 1977, and were obtained from the Department of Commerce OBERS model. Base year emissions data were for 1975, and were obtained from the National Emission Data System (NEDS). Electric utility growth projections were based on the Recharge Capacity Projection System (RECAPS) output generated both with and without EHV use. Emission and air quality control levels were based on new source performance standards proposed in 1978. Emissions from facilities built prior to 1978 were assumed to be controlled to the level defined in NEDS. These projections, therefore, do not fully reflect the effect of the 1977 Amendments to the Clean Air Act which require that states submit revised State Implementation Plans (SIPS) which assure that future air quality will satisfy the national primary standard. Analysis was based on the 24 most populated air quality control regions (AQCRs) in the United States. The results reflect population-weighted averages. The specific pollution indicators were calculated using a formula developed for SEAS which weights each major pollutant type according to impact on human health to arrive at a single composite figure.



Source: Regional Emissions Projection System (REPS), General Research Corporation

Assumptions: Industrial growth projections were for 1977, and were obtained from the Department of Commerce OBERS model. Base year emissions data were for 1975, and were obtained from the National Emission Data System (NEDS). Electric utility growth projections were based on the Recharge Capacity Projection System (RECAPS) output generated both with and without EHV use. Emission and air quality control levels were based on new source performance standards proposed or promulgated in 1978. Analysis was based on the 24 most populated air quality control regions (AQCRs) in the United States. The results reflect population-weighted averages.

Figure 7.4 Air Quality Projections Without EHVs



Source: Regional Emissions Projection System (REPS), General Research Corporation

Assumptions: Industrial growth projcetions were for 1977, and were obtained from the Department of Commerce OBERS model. Base year emissions data were for 1975, and were obtained from the National Emission Data System (NEDS). Electric utility growth projections were based on the Recharge Capacity Projection System (RECAPS) output generated both with and without EHV use. Emission and air quality control levels were based on new source performance standards proposed or promulgated in 1978. Analysis was based on the 24 most populated air quality control regions (AQCRs) in the United States. The results reflect population-weighted averages.

Figure 7.5 Percent Change in Air Quality with 20 Percent Electrification of Light-Duty Vehicular Travel

to the human environment, particularly those resulting from the use of transportation vehicles.[3] As a result, various regulations have been established to reduce truck, bus, and motorcycle noise (Table 7.6). Regulations have not yet been established for automobiles. Although automobiles account for more than 90 percent of all urban traffic, their contribution to total urban traffic noise in the mid-1970s was little more than half. Consequently, a reduction in automobile noise would have little noticeable impact unless also accompanied by a reduction in truck, bus, and motorcycle noise.[4]

It is interesting to note that the recent trend toward smaller, more fuel-efficient vehicles may increase the contribution of automobiles to the overall noise problem. Automobiles powered by four-cylinder gasoline and diesel engines produce from 3 to 5 dB(A) more noise than conventional V-8 and six-cylinder engines.

Different levels of urban traffic noise affect different numbers of people (Table 7.7). It is estimated that nearly 95 million people are subjected to noise levels which begin to affect intelligibility of speech (55 dB day-night equivalent sound level). Although only slightly more than one million people are subjected to relatively high noise levels (75 dB), the resulting impacts can be much worse, sometimes affecting human behavior. In fact, at sound levels above 85 dB, permanent hearing damage can occur if exposure is over a long period.

Electric propulsion of automobiles is inherently quiet. When operating in the electric mode, EHVs do not use an engine, radiator fan, air intake, or exhaust, all of which are major noise producers in a conventional car. The electric motor of the EHV is typically much quieter. A recent test by the Japanese government comparing electric and conventional economy cars found electrics to be 15-25 percent quieter when stopped, accelerating, and passing (Fig. 7.6).[5] Even when traveling at constant speed, the electrics were about 5 percent quieter.

Consequently, desirable reductions in traffic noise are likely with the widespread use of EHVs. Even though conventional cars may be made considerably quieter in the future, substitution of EHVs could reduce the future level of noise impact substantially (Fig. 7.7).[6] After current regulations have had their effects on truck, bus, and motorcycle noise, the overall noise impact would be reduced to 57 percent of the 1975 level, if conventional autos grow no noisier. EHV use could reduce urban traffic noise impact to as little as 27 percent of the 1975 level (at 100 percent EHV market penetration).

7.3.3 Health and Safety

Large-scale use of EHVs might affect public health and safety because of increased generation of electric power, modifications in vehicular design and capability, and changes in industrial working conditions, primarily in the battery manufacturing industry. However, the

TABLE 7.6

VEHICULAR NOISE LEVEL AND TRAFFIC MIX

Vehicle	Median Passby Noise Level at 50 feet, dB(A)[1]		Percent of Urban Traffic
	Present	After Regulation[2]	
Heavy-Duty Trucks	85	71	1.0
Medium-Duty Trucks	77	71	6.0
Buses	79	75	0.5
Motorcycles	82	78	1.0
Automobiles	65	to be determined	91.5

Source: "Air Quality, Noise, and Health," Report of the Interagency Task Force on Motor Vehicle Goals Beyond 1980, US Department of Transportation, TAD-443.1, March 1976. Tables 6-5 and 6-6.

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[1] Median automotive "passby noise" is expressed in terms of an A-weighted sound level (decibels), which ordinarily varies considerably with time, and is indicated directly by standard sound level meters. The A-weighting emphasizes sounds in the middle frequencies to which the human ear is most responsive. In quiet areas at quiet times of day, A-weighted sound levels may be as low as 30-40 dB(A), while in very noise areas, they may exceed 100 dB(A). The levels identified are composites which reflect the average level during cruise and acceleration conditions representative of urban driving.

[2] Levels expected by 1990.

TABLE 7.7

ESTIMATED NUMBER OF PEOPLE SUBJECTED TO URBAN TRAFFIC NOISE

At or Above Outdoor Day-Night Equivalent Sound Level, dB[1]	People, millions
55	93.4
60	59.0
65	24.3
70	6.9
75	1.3

Source: "Air Quality, Noise, and Health," Report of a Panel of the Interagency Task Force on Motor Vehicle Goals Beyond 1980, US Department of Transportation TAD-443.1, March 1976. Table 6-4.

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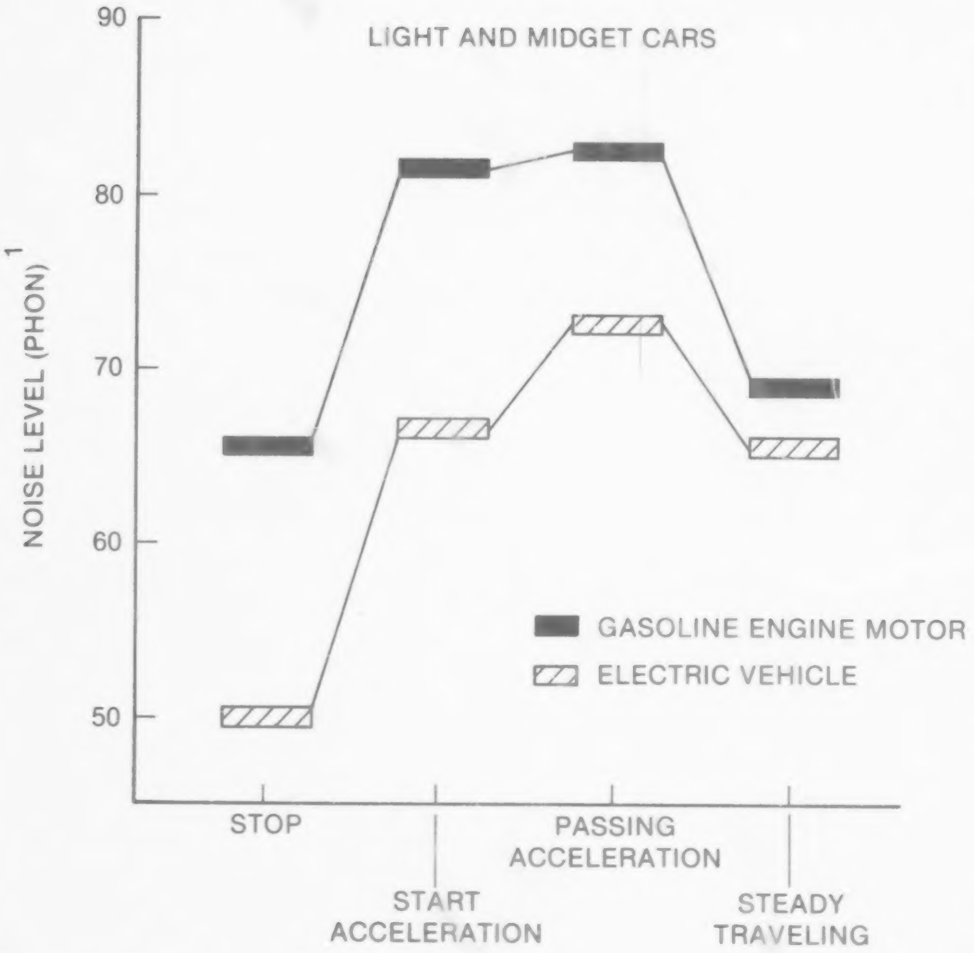
[1] The customary measure of the impact of urban traffic noise is computed from outdoor day-night equivalent sound levels. The computation combines the level of traffic noise with the number of people exposed at that level. It assumes that adverse effects of noise begin at a specific criterion, 55 dB, and that they reach a 100-percent level at 75 dB. At day-night equivalent sound levels of 55 dB outdoors, indoor levels may be near 45 dB, allowing 100 percent intelligibility for all types of speech. After a 20-dB increase above this level, intelligibility begins to drop very rapidly with further increases, supporting the assumption that few people would be adversely impacted at 55 dB, while at 75 dB, virtually everybody would be adversely affected.



Source: Research and Development of Electric Vehicles in Japan, Agency of Industrial Science and Technology, Ministry of International Trade & Industry and Society of Automotive Engineers of Japan, Inc. 1977.

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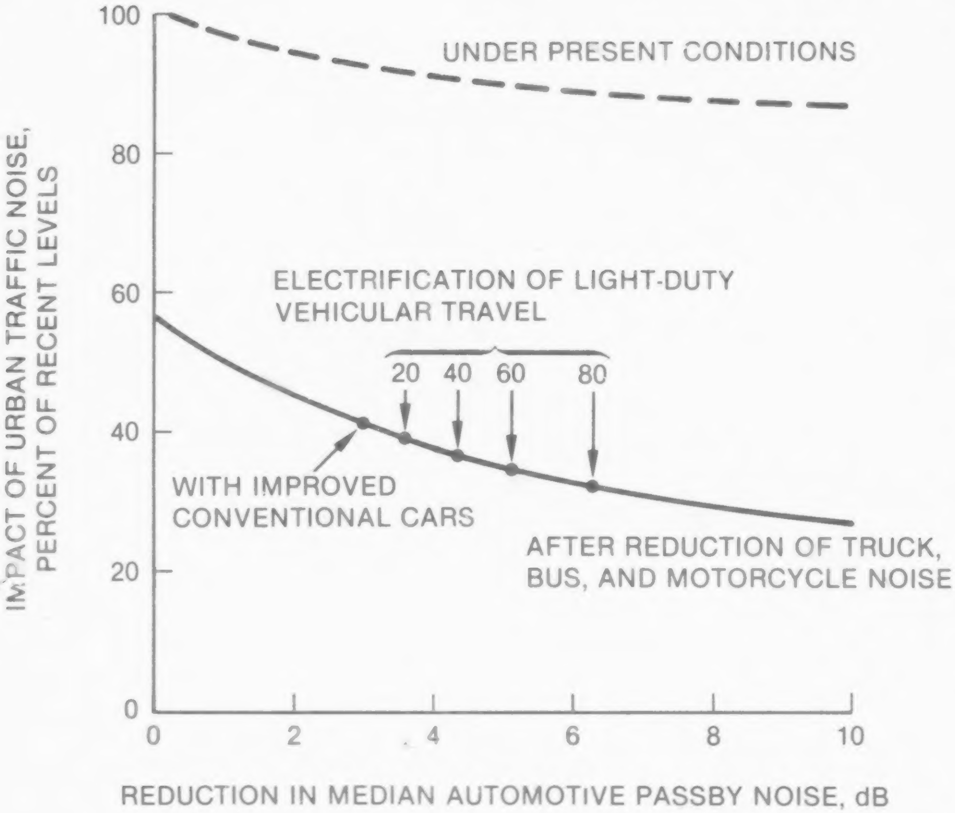
[1] Noise levels are stated in phons, a unit of noise measurement which is technically different, but similar to, the dB(A) measure predominantly used in the US.

Figure 7.6 Measured Noise of Japanese Test Cars



Source: W. Hamilton, Electric Automobiles, McGraw-Hill Book Company, New York, 1979.

Assumptions: Noise standards for trucks, buses, and motorcycles are assumed to be in effect. Noise from sources other than transportation vehicles are assumed to remain constant. Data used to prepare this figure are for 1975. Improved conventional cars are expected to be about 3 dB quieter than present conventional cars. Electric cars are assumed to be 3.3 dB quieter than improved conventional cars.

Figure 7.7 Effects of Electric Cars on Urban Auto Noise and Traffic Noise Impact

impact is expected to be small at 20-percent electrification of light-duty vehicular travel.

The major factor to be considered is the effect of increased generation of electric power to recharge EHVs. If EHVs were recharged during off-peak hours, about 0.5 to 0.6 quadrillion additional BTUs would be required to electrify 20 percent of light-duty vehicular travel each year in the 1980-2010 time frame. However, since annual demand without EHVs is projected to increase over the same period, the contribution of EHVs to total electricity demand will decrease each year. In 1990, for example, the percentage of total demand attributed to EHVs would be 4.5 percent, but would drop to 2.1 percent by 2010.

Although it is not expected that 20-percent electrification of light-duty vehicular travel would have much impact on public health and safety, expert opinion on the impact of any increase in power generation is divided, and much research in this area is currently being conducted. Consequently, a brief discussion of the major issues is presented here.

The detrimental effects of power plants on public health and safety have been repeatedly analyzed in recent years, largely because of the fierce public debate over the desirability of nuclear power.[7] The analyses show clearly that nuclear plants are not alone in presenting risks to health and safety; coal plants are also detrimental, primarily due to increased SO_x emissions (see Sec. 7.3.1).[8], [9], [10] While some parts of these analyses are relatively secure, other very important parts require assumptions which are little more than guesswork. It has therefore been impossible to determine conclusively whether nuclear plants are preferable to coal plants. It is clear, however, that use of EHVs would increase whatever the problems of nuclear and coal plants may be, even if only slightly.

Overall, there seems little question that by requiring added generation of electricity, EHVs could detract slightly from public health and safety. The effects, however, will surely be far less than proportionate to the extra electric energy required by EHVs. Since no additional facilities would be required, other than those already planned to satisfy normal future demand, EHVs need not cause an increase in the number of nuclear reactors subject to accidents. Moreover, where diversion of plutonium and sabotage of reactors are the serious risks, they may not be increased significantly by EHVs. If reactors are already numerous and shipments of nuclear materials among them are already frequent, additional shipments may have little practical consequence for would-be terrorists or saboteurs already presented with abundant opportunities for action.

Another detrimental impact of the generation of additional electric power using fossil fuels, primarily coal, is the creation of more acid rain. Large fossil fuel plants emit sulfur oxides and nitrogen oxides high into the atmosphere where they may be transported thousands of miles by prevailing winds. Such pollutants are often converted into sulfuric and nitric acids which eventually wash out in rain, sleet, hail, and snow. Although acid rain does not directly affect human health, it poses a real threat to both plants and wildlife which form the bulk of the eco-system. Many studies are currently being funded by the federal government to quantify the scope and severity of the acid rain problem, and to formulate effective ways to eliminate or reduce its impact. Although the technology needed to more strictly control power plant emissions currently exists, it is quite expensive, thus creating resistance by the electric utilities.

Crash safety of EHVs is currently in the early stages of research and development. However, it appears that structural design to accommodate a heavy set of batteries, as opposed to a fuel tank filled with gasoline, is well within current technology. In fact, batteries containing acids, chlorine, and other potentially hazardous chemicals may be less dangerous than a fuel tank filled with gasoline or diesel. This is often overlooked because gasoline is commonplace and accepted; but it is extremely flammable and can explode or burn upon impact. Since it is likely that EHVs will have to meet the same safety standards as conventional vehicles and will equal the lower-performance conventional vehicles in acceleration, their overall influence on the number and severity of auto accidents should be small. In fact, if lower-capability EHVs encourage more prudent driving, there may be positive benefits from their use. There are possibilities of electrical shock, explosive fires, or chemical and toxic gas hazards when operating and recharging EHVs, but these can be minimized through proper engineering and design.

Increased battery production using a variety of chemicals unfamiliar to the battery manufacturing industry could create new safety concerns. However, careful design and construction of new facilities and close monitoring by appropriate federal agencies should minimize the risks.

7.3.4 Thermal Pollution

EHVs would be about as efficient overall as conventional vehicles fueled from petroleum, if typical losses in electric utilities are included. They would thus have little effect on total energy used and eventually released as heat into the environment. In conventional vehicles, however, almost all this heat is evolved when and where the vehicles are driven. In EHVs, only about a third of the total heat would be released in this manner. The remainder would be evolved at a relatively few power plants during recharging, and concentrated releases of heat can potentially produce changes in local weather patterns. However, it is not expected that 20-percent electrification of light-duty vehicular travel would result in any significant impact on thermal pollution.

7.3.5 Waste Oil

Lubricating oil in the crankcases of automotive engines is periodically drained and replaced with clean oil. The old oil is often collected and used for boiler fuel, for road oiling, for asphalt, and for other purposes. Nevertheless, substantial quantities of oil are more or less indiscriminately dumped into the environment,[14] particularly in rural areas where collection is presently unprofitable.

EHVs have no crankcases and require no periodic oil changes. To the extent that they were used, the problem of discarded oil from automobiles would be reduced. Overall, 20-percent electrification of light-duty vehicular travel in the United States would eliminate the use of about 130 million gallons of oil per year for automobile crankcase use. This amounts to almost 15 percent of all automotive demand for lubricating oils and 7 percent of all demand for lubricating oils.

7.4 ECONOMY

The substitution of electric and hybrid vehicles for conventional automobiles could affect the economy in several major ways. Purchase and operating costs affect consumers, changes in economic activity to manufacture, sell, and service automobiles affect employment, the expansion and retirement of various production facilities affect business capital investments, and changes in the importation of petroleum and battery materials affect the national balance of payments.

7.4.1 Consumers

Perhaps the most pervasive effect of EHVs in the near term would be the higher initial and life-cycle costs to motorists. Even with longer life and inexpensive electricity, near-term EHVs are still more expensive than conventional vehicles on a life-cycle cost basis at today's gasoline prices. If consumers are forced to spend more on transportation, less of their disposable income is available for other purchases. This decrease in non-automotive expenditures would be felt throughout the economy. The higher cost of electric and hybrid vehicles might make their purchase less attractive to consumers. If the government wished to encourage electric or hybrid vehicle use, it might have to subsidize either the producers or the consumers, which would affect the national budget. In the future, an increase in gasoline price could bring the cost of EHV use more in line with the cost of using conventional vehicles, thereby negating these economic effects on consumers. Increases in battery life or decreases in battery price beyond those projected here are unlikely to reduce EHV costs by more than a small amount.

7.4.2 Capital Investment

Capital investment will be necessary to expand the production capacity to mine and process battery materials, to manufacture propulsion batteries, motors, controllers, and chargers, and to recycle battery materials. Little, if any, increase in investment for new electric utility capacity will be required, assuming overnight, off-peak recharging. Capital equipment associated with the manufacturing of internal combustion engines would be retired. However, the penetration of electric and hybrid vehicles will probably be accomplished over a period of years, during which portions of the aging capital equipment would be retired anyway. Major portions of the facilities and equipment used to produce conventional vehicles can be adapted for use in the production of electric and hybrid vehicles. The magnitude of capital investment and retirement has not been estimated.

7.4.3 Employment

The switch from conventional to electric and hybrid vehicles would alter the employment in those economic sectors involved in production, sales, and service. Overall, only 3.75 percent of US employment in 1974 was in potentially affected industries, with payrolls amounting to only 4.5 percent of the national total.

Major increases in employment will occur in industries associated with propulsion batteries, including the mining and processing of materials, the manufacturing and sale of the batteries themselves, and the recycling of the batteries to recover usable materials. Employment would also increase in sectors involved in the production and servicing of motors, controllers, and chargers. More people are involved in the distribution and sales of vehicles than are involved in their production. Distribution and sales of vehicles would continue with little change; therefore employment and payrolls in these sectors would be little effected.

Only some of the jobs pertaining to the manufacturing and servicing of internal combustion engines will be lost if hybrid vehicles replace conventional vehicles. Production workers will still be required to manufacture internal combustion engines and other vehicle parts, mechanics will still be required to service the ICE and other vehicle parts for which they have already been trained, and some service station attendants will still be needed to pump gasoline. The level of ICE-related work would depend on hybrid vehicle design: hybrids most like ICE cars (high-performance hybrids) would lead to modest changes, whereas hybrids most like electric cars (range-extension hybrids) would lead to larger changes.

The maximum dislocation of jobs would occur if all conventional vehicles were replaced by electric vehicles, since all internal combustion engine production and service would disappear, gasoline production and sales would vastly decrease, and huge increases would occur in industries associated with propulsion batteries. If all vehicles were electric in the year 2000, over 800,000 jobs would be lost in ICE-related industries. Over half of these lost jobs would be from automotive service stations. Other sectors experiencing large employment losses include: automotive repair shops (-143,000), automotive supply stores (-107,000), motor vehicle parts distribution (-84,000), and motor vehicle body and parts manufacturing (-54,000). However, job losses in these industries will be more than offset by employment gains in electrical equipment, mining, and battery manufacture, distribution, and sales. If all vehicles in the year 2000 contained lead-acid batteries, an estimated 850,000 new jobs would have been created; if lithium-metal sulfide batteries are used, newly created jobs would number over two million (Table 7.8). Although shifts between economic sectors occur, the overall change in employment and payrolls is insignificant, even in the extreme case of 100 percent electric vehicle penetration, amounting to about a one-percent increase (Tables 7.9 and 7.10).

7.4.4 Balance of Trade

One of the major goals of EHV use is the reduction of petroleum imports. Such a reduction would improve the nation's balance of trade. However, savings in petroleum imports will be offset to some extent by imports of battery materials.

Assuming the current percentage imports of battery materials and using their 1979 price, the cost of imported materials to electrify 20 percent of light-duty vehicular travel in the United States (25 percent of the US light-duty vehicle fleet) would be approximately 3.8 billion dollars if lead-acid batteries are used, or 20.3 billion dollars for nickel-zinc batteries (Table 7.11). Few or no imports would be required for lithium-metal sulfide batteries. These imports can be compared with a savings of about 220 million barrels of oil annually in 2000, which, at a nominal price of $30 per barrel for imported petroleum, yields a 6.6 billion dollar annual decrease in imports.[12]

Thus it appears that although initial requirements for battery material might add considerably to United States imports, their value would be recouped in a few years through reduced oil imports. There are many uncertainties, however, including the amount of imported petroleum used to generate electricity for recharging electric and hybrid vehicles, the extent to which increased demand for battery materials affect their price, and the extent to which additional demand beyond baseline projections for battery materials would be met by additional imports. The actions of cartels controlling petroleum, and perhaps some battery materials, are impossible to project.

The use of electric and hybrid vehicles is likely to improve the balance of payments in the future. By the year 2000, only a small percentage of fuel used to generate recharge electricity will be petroleum. In time, United States mining operations will be able to supply a greater percentage of battery materials, cutting down on imports if their prices have increased substantially. One of the major factors leading to a reduction in the balance of payments will be the development of efficient recycling which will develop once a significant

TABLE 7.8

IMPACTS OF 100 PERCENT USE OF ELECTRIC CARS ON EMPLOYMENT AND PAYROLL, BY INDUSTRY

Standard Industrial Classification	Industry	Employment Change, thousands			Payroll Change, millions of 1977 dollars		
		1980	1990	2000	1980	1990	2000
(independent of battery type)							
3592	Carburetor, piston, valve manufacturing	-24	-31	-37	-345	-450	-554
3622	Electric controls manufacturing	33	38	41	425	497	459
3694	ICE electric equipment manufacturing	15	14	11	425	230	187
3711,3714	Motor vehicle body and parts manufacturing	-56	-57	-54	-1000	-1173	1227
5012	Motor vehicle parts distribution	-57	-55	-84	-854	-819	-1360
5171,5172	Petroleum wholesalers	-35	-22	-28	-505	-339	-455
5531	Automotive supply stores	-67	-87	-107	-640	-858	-1075
5541	Automotive service stations	-293	-350	-410	-1741	-2112	-2499
7538,7539	Automotive repair shops	-93	-118	-143	-757	-948	-1141
	SUBTOTAL	-576	-667	-810	-5191	-5972	-7665
(lead-acid batteries)							
1031,3332	Lead and zinc mining, smelting	73	86	107	994	1,254	1,665
3691	Storage battery manufacturing	196	214	224	2,648	2,985	3,212
-	Battery distribution and sales	432	454	467	5,753	6,536	7,099
	SUBTOTAL	701	754	798	9,395	10,775	11,976
(nickel-zinc batteries)							
1031,3332	Lead and zinc mining and smelting	55	60	57	744	868	892
-	Nickel and cobalt mining	43	37	35	796	915	1,332
3691	Storage battery manufacturing	518	587	622	6,996	8,197	8,903
-	Battery distribution and sales	1,084	1,140	1,172	14,438	16,404	17,818
	SUBTOTAL	1,700	1,823	1,887	22,973	26,384	28,946
(lithium-sulfur batteries)							
-	Nickel and cobalt mining			11			408
-	Lithium mining			27			863
-	Molybdenum mining			12			402
3691	Storage battery manufacturing			699			10,005
-	Battery distribution and sales			1,317			20,010
	SUBTOTAL			2,066			31,694

Baseline projections made by least-squares regression analysis of historical data published in County Business Patterns. Adjustments were made to the portion of activity estimated to be affected by electric vehicle production and use.

TABLE 7.9

IMPACTS OF 100 PERCENT USE OF ELECTRIC CARS ON TOTAL EMPLOYMENT IN INDUSTRIES DIRECTLY AFFECTED

Type of Battery Used In Electric Cars	Employment Change in Affected Industries					
	Thousands			Percent US Employment		
	1980	1990	2000	1980	1990	2000
Lead-Acid	126	87	-12	0.14	0.09	-0.01
Nickel-Zinc	1124	1156	1077	1.27	1.19	1.02
Lithium-Metal Sulfide	1287	1319	1255	1.45	1.36	1.19

TABLE 7.10

IMPACTS OF 100 PERCENT USE OF ELECTRIC CARS ON TOTAL PAYROLL IN INDUSTRIES DIRECTLY AFFECTED

Type of Battery Used In Electric Cars	Payroll Change in Affected Industries					
	Millions of 1977 Dollars			Percent US Payroll		
	1980	1990	2000	1980	1990	2000
Lead-Acid	4204	4803	4311	0.28	0.23	0.14
Nickel-Zinc	17782	20412	21281	1.19	0.97	0.70
Lithium-Metal Sulfide	19949	22813	24029	1.33	1.08	0.79

Basline projections made by least-squares regression analysis of historical employment and payroll data published in County Business Patterns. Adjustments were made to the portion of activity estimated to be affected by electric vehicle production and use.

TABLE 7.11

NOMINAL CUMULATIVE COST OF IMPORTED MATERIALS TO ELECTRIFY 20 PERCENT OF LIGHT-DUTY VEHICULAR TRAVEL IN THE UNITED STATES

Battery	Material Requirement, lb × 10^6	Percent Imported*	1979 Price per Pound†	Cost of Imports, billions of dollars
Lead-Acid:				
Lead	35.0	30	0.36	3.8
Nickel-Zinc:				
Nickel	10.0	50	2.24	11.2
Zinc	6.0	50	0.20	0.6
Cobalt	0.5	100	16.95	8.5

*Current percent imported in absence of EHVs

†Source: L. G. Hill, The Impact of EHVs on Factor Prices and the Balance of Trade, Discussion Draft 16, Argonne National Laboratory, Illinois, October 1979.

level of EHV penetration is reached. Recycling will substantially reduce the demand for new battery materials.

7.5 RESOURCES

7.5.1 Imports of Battery Materials

The United States currently imports nearly all the cobalt, graphite, and aluminum ore and over half of its nickel.[13] Dependence on foreign sources for supplies of battery materials involves significant political considerations, especially if the reserves are concentrated in one or a few locations. The political stability of exporting countries affects the reliability of continued supply. Concentration of resources opens the possibility of market control in the form of monopolies or cartels which could manipulate the price and availability of materials required for batteries. A nickel cartel could be as damaging to an electric vehicle industry based on nickel-zinc batteries as the OPEC oil cartel is to the present auto transportation system. Fortunately, most battery materials are imported from Western-aligned nations, the major exception being cobalt, the majority of which is imported from Zaire and other politically unstable African countries (Table 7.12).

Of all the battery materials considered in this report, the United States is self-sufficient in or imports only small quantities of boron,

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TABLE 7.12

LOCATION OF BATTERY MATERIAL RESERVES AND RESOURCES

Material/Location	Percent of World Reserves	Percent of World Resources
Aluminum		
Australia	26	21
Guinea	26	17
Brazil	16	17
Jamaica	6	4
Greece	4	3
Cameroon	4	5
Boron		
United States	25	
USSR	25	
Turkey	25	
China	13	
Argentina	6	
Chile	6	
Chlorine		
United States		
Many Others		
Cobalt		
Zaire	28	31
Oceania	27	36
Zambia	14	14
Cuba	14	43
Canada	7	10
United States	--	31
Copper		
United States	20	20
Chile	20	11
USSR	9	6
Canada	9	8
Asia	7	10
Sea Nodules	--	20
Graphite		
Mexico		
Malagasy Republic		
Sri Lanka		
United States		
Iron		
USSR	31	27
Brazil	17	13
Canada	12	13
Australia	10	9
India	6	4
United States	4	8
Lead		
United States	36	36
Canada	12	12
USSR	18	11
Australia	18	9
Lithium		
United States	44	44
USSR	27	19
Canada	13	14
Africa	13	10
Nickel		
New Caledonia	44	22
Canada	16	15
USSR	10	8
Australia	9	6
Indonesia	5	5
Cuba	6	16
Phillipines	2	6
United States	0.003	12
Sulfur		
Asia/Near East	30	17
Canada	21	28
United States	12	12
USSR	8	11
Spain	1	9
Zinc		
Canada	23	20
United States	20	19
Australia	12	13
USSR	8	9
Ireland	5	4

Source: US Bureau of Mines, Mineral Facts and Problems, 1975 Edition, US Government Printing Office, Washington, D.C. 1976.

chlorine, copper, lithium, and sulfur. Therefore, no problems in obtaining these materials are foreseen for the electric vehicle industry, although significant expansion of US lithium production will be required. While the United States has large resources of most battery materials, in the short run at least, it will continue to rely on foreign sources to supply battery materials. One reason for continued importation of these materials is that they can be obtained at less cost from countries where labor is less expensive than in the United States. Another reason is that higher-grade ores can be found outside the United States. In the cases of aluminum, graphite, and nickel, new technologies would need to be developed before deposits in the United States could be economically utilized. If the United States attempted self-sufficiency, costs would most likely increase significantly because of the use of more expensive labor, the development of new technologies, and the capital cost involved in expanding domestic industries.

Lead-Acid Batteries. The primary materials required for the production of lead-acid batteries are lead and sulfur. The United States now produces most of the sulfur needed domestically. Environmental restrictions will enforce a substantial production of sulfur recovered from petroleum refining, coal combustion, and other sources, so the supply of sulfur for use in batteries should be plentiful.

The United States produces about two-thirds of the lead needed to satisfy domestic primary demand (for new rather than recycled material), but substantial increases in mining and smelting capacity would be required to continue supplying this percentage of projected primary demand if mass production of lead-acid propulsion batteries occurs.[14] Therefore, demand for lead by battery manufacturers would probably precipitate an increase in lead imports, at least in the short run, until recycling reduces the primary demand for lead for EHV batteries.

Nickel-Iron and Nickel-Zinc Batteries. The nickel-iron battery requires principally nickel and iron, plus smaller amounts of cobalt (used in the nickel electrodes), copper, lithium, and potassium. Nickel-zinc batteries require the same materials except for the substitution of zinc for iron. Nickel, cobalt, and some of the iron or zinc will be imported for these batteries.

Domestic primary production supplies only about 10 percent of the demand for nickel in the United States, with scrap accounting for another 20 to 30 percent.[13] Over half of the nickel supply is imported, mainly from Canada. The potential supply of nickel from domestic sources is high, but production will require marked improvement over current technology for extracting nickel from low-grade ores. Deep sea mining is another possible source.

Nearly all of the cobalt used in the United States is imported, about 75 percent from Zaire. The political instability of nations in this area has recently caused interruptions in production. There is also evidence of the existence of a cobalt cartel, which could control cobalt prices and supplies.[15] Expansion of United States cobalt production is predicted, especially if nickel production is increased, since cobalt is a by-product of nickel mining, or if deep sea mining is implemented.

Approximately one-third of iron ore required by the United States iron and steel industries is imported. The price and availability of foreign ores may be influenced by organizations of producers. The USSR has the world's largest reserves and resources of iron ore, but it is also abundant in the western world.

In the recent past, the United States has imported one-third to one-half of its zinc requirements, principally from Canada. Zinc demand for battery materials could be met with existing reserves, but significant expansion of smelting capacity would be required.

Zinc-Chlorine Batteries. In addition to zinc, which is discussed above, the primary materials needed for the zinc-chlorine battery are chlorine and graphite. Chlorine can be readily supplied domestically, but the United States' demand for graphite is almost entirely fulfilled by imports from Mexico, Sri Lanka, and the Malagasy Republic.[13] The United States could increase its output of graphite, but at some expense to reactivate domestic sources. Graphite can be manufactured, but with present technologies the product is not suitable for all uses. Grades of graphite differ considerably, so some level of graphite importation will probably continue.

Lithium-Metal Sulfide Batteries. Aluminum, boron, chlorine, copper, iron, lithium, potassium, and sulfur are used in lithium-metal sulfide batteries. All the materials can be supplied domestically except some of the iron and aluminum. The United States imports about 90 percent of the raw materials (buaxite and alumina) required to produce aluminum. Principal exporting countries are Australia and Jamaica. Battery requirements for aluminum are a very small portion of total United States demand, so EHV production will not significantly affect aluminum imports. The United States has large deposits of lithium, most of which are undeveloped because of low demand. However, the amount of lithium needed for lithium-metal sulfide batteries will require extensive development of these resources.

7.5.2 Battery Materials Versus Petroleum

All natural resources exist in finite amounts. Increased demand for battery materials would spur exploration for new deposits, but the amount of material in these deposits is unknown. Ultimately, battery materials may not be any more plentiful than petroleum if the world switches to electric and hybrid vehicles. However, there is a major difference between the use of gasoline and the use of batteries for transportation propulsion: gasoline burns and is gone, requiring continual new supplies; battery materials can be recycled, and therefore new materials would be needed only to enlarge the fleet and to replace small amounts lost in recycling.

The United States probably has enough resources to be self-sufficient in the supply of most materials for batteries. However, self-sufficiency would involve considerable (presently unquantifiable) expenditures on the development of new technologies to process low-grade ores (especially in the cases of nickel and cobalt for nickel-iron and nickel-zinc batteries and graphite for zinc-chloride batteries) and on exploration and capital equipment to mine and process new resources. Such expenditures would probably be unwarranted if exporting countries maintain stable governments and good trade relations with the United States continue. The probability of continuing supplies from exporting countries is high, and the likelihood of cartel actions is low, except perhaps in the case of cobalt.

7.5.3 Effect on Prices of Battery Materials

Historically, real prices of most minerals and metals have not increased; that is, their cost trends have been stable or downward relative to the costs of other goods and services. The sharp rise in the cost of energy and the expense of pollution control in the 1970s have caused the cost of materials to rise recently. Continued exploration for new deposits and improved technologies for processing lower-grade deposits offset the depletion of known reserves, thereby mitigating price increases which could arise from the scarcity of materials, although materials from lower-grade deposits may be more expensive.

A recent study by Charles River Associates[15] has concluded that estimated reserves of battery materials are sufficient to satisfy the cumulative demand for these materials, even with widespread use of EHVs, so that major price increases are not expected to occur, except in the cases of lithium, nickel, and cobalt.

High levels of EHV production would create heavy demands for lithium (if lithium-metal sulfide batteries are produced), or for nickel and cobalt (if nickel-iron or nickel-zinc batteries are produced), which could exert significant upward pressure on the long-run price trends for these materials. Price effects have not been quantitatively estimated, but if producers were given sufficient lead time* to increase exploration and production capacity, the long-run price increases seem unlikely to exceed 10 to 20 percent. However, extremely rapid increases in production of lithium, nickel, or cobalt, without time to plan an orderly expansion, could result in a doubling or more of prices for these materials.[15]

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* "Sufficient lead time" is very difficult to quantify. If production requires only the reopening of mines which have been shut down, sufficient lead time might be a year. If exploration and the erection of mining and processing equipment are required, five years might be a minimum time before production begins. If new technologies must be developed (as would be the case if domestic nickel, graphite, and aluminum ore deposits were to be exploited), the lead time required might be ten years or more. Another, perhaps more critical, consideration exists. Private firms will not begin to develop new sources until the increased demand has raised prices to the point where they can expect a reasonable return on investment.

These predictions of price trends assume continued availability of imports. A disruption of the world market for these materials, either because of political upheaval in exporting countries or the formation of cartels, could result in price fluctuations which are impossible to predict.

7.5.4 Competing Demands for Battery Materials

Massive demands for battery materials for EHVs could drive up costs and reduce supplies of materials for other applications. The relative demand for materials for EHV batteries and other uses are discussed in Sec. 5.4.3.

The principal uses for lead have been in transportation, mostly in storage batteries for starting, lighting, and ignition; in anti-knock compounds added to gasoline (which is being phased out); and as sheathing for electrical cable. Lead is also used in paints, ammunition, and construction.

Nickel is widely used to make alloys which are strong, corrosion-resistant, and useful over a wide temperature range. Such materials are of strategic importance, used in aircraft, ships, motor vehicles, and electrical machinery. The chemical and petroleum industries are the principal end users of nickel, chiefly in the form of alloys. Substitutes for nickel exist for almost all its uses, but they are generally more expensive and less effective.

Zinc is third among non-ferrous metals in terms of world consumption, following only copper and aluminum. It is used for alloying, protective coatings (galvanizing), and in making rubber and paints. Principal uses for cobalt are in heat-, abrasion-, and corrosion-resistant materials, high-strength materials, and permanent magnets. Cobalt is used in permanent magnets, aircraft and surface vehicle engines, machine tools, construction and mining, and paints and chemicals.

The largest uses of graphite are for foundry facings to provide for clean and easy recovery of metal castings, and for raising the carbon content of steel. Graphite is also used in heat-resistant, non-metallic ceramic materials, and lubricants and packings. It may also find increasing use in graphite-reinforced plastics. The best-known uses of graphite, in pencils and in brake and clutch linings, account for only about 9 percent of the demand for graphite.

Lithium compounds are used in the electrolyte of cells for producing aluminum and in ceramics, glass, and lubricants. Lithium metal, which accounts for only a small portion of current lithium demand, is used for the manufacture of synthetic rubber, Vitamin A, and anodes for premium primary batteries offering very high energy density and long shelf life. Though the demand for lithium is presently very small, rapid growth in demand is projected, though there is uncertainty about the amount. The generation of power through nuclear fusion, if commercially successful, could require amounts of lithium close to today's total identified resources, and substitution of other materials for this purpose is unlikely.

7.6 TRANSPORTATION

EHVs can satisfy nearly all normal driving needs of the general public, particularly in urban areas where travel distances and average speeds are moderate. Motorists who purchase and utilize EHVs will experience both advantages and disadvantages compared to owners of conventional vehicles. In general, EHVs will provide owners with the convenience of recharging at home using an assured electrical power supply. They will also be quieter to operate and may be more reliable and maintainable. The primary disadvantages will be that initial costs will be higher and life-cycle costs will be greater, at least until advanced batteries become commercially available by 2000 or until real prices of motor fuels rise substantially. Electrics, unlike hybrids, will also have less range than conventional vehicles.

Most EHV owners who live in single-family residences would be able to obtain electrical outlets for recharging at overnight parking places. These people would thus enjoy the convenience of at-home recharging instead of waiting in lines at service stations if the availability of gasoline again becomes critical. This is extremely important because the recent gasoline supply interruptions have clearly demonstrated that motorists place a high premium on minimizing the necessity of waiting in service station lines. Although hybrid vehicles will occasionally require gasoline, the vehicle's range in electric mode will provide the motorist with mobility in the total absence of gasoline, and with the opportunity to be quite selective in determining the best time to refuel.

Since EHVs are substantially quieter and more vibration-free than conventional vehicles, motorists will experience a somewhat smoother, more silent ride. In addition, the inherent reliability of electric motors and controllers in comparison to internal combustion engines may provide EHV owners with relief from many service and reliability problems. Recent figures for on-the-road failures of automobiles corroborate this expectation (Table 7.13). Nearly 85 percent of all on-the-road failures can be attributed to the internal combustion engine system.

TABLE 7.13

ON-THE-ROAD FAILURES OF AUTOMOBILES

Cause of Failure	Frequency, percent
Engine	8.6
Fuel System	13.6
Cooling System	27.3
Ignition System	18.2
Starting/Charging System	16.4
Total - Engine Systems	84.1
Transmission	5.7
Driveline	1.7
Brakes	1.2
Suspension	1.4
Electrical System	3.5
Other	2.4
Total - Remainder of Car	15.9

Source: William Hatch et al., Analysis of On-Road Failure Data, US Department of Transportation, DOT-HS-802 360, May 1977.

Battery reliability is also a legitimate concern because, until now, the industry has concentrated primarily on the production of lead-acid batteries used to start internal combustion engines. The widespread use of EHVs will require the production of a variety of new types of propulsion batteries which will experience greater loads under more severe conditions. Since the reliability of these new batteries has not yet been established, some concern is warranted. However, careful design, engineering, and production of batteries could result in total EHV systems that are more reliable than comparable conventional vehicles.

Other types of service and repair of components other than the electrical system and ICE should be similar for EHVs and conventional vehicles.

Hybrid systems may not be quite as reliable as electrics because they are more complex. However, this depends largely on the particular design selected for the vehicle. In the case of a simple range-extension hybrid, reliability may be comparable to that of an electric. In more complex designs, it may be lower. In either case, however, actual availability of the vehicle for driving may be greater than that of an electric because of the possibility of operating in either of two different modes if one fails. If the ICE fails, operation can continue in the electric mode. If the electric propulsion system fails, the ICE system can be used to power the vehicle. Only in those cases where both systems fail or the failure of one system precludes the operation of the other would the vehicle be totally disabled.

Both electric and hybrid vehicles may also be more maintainable than comparable conventional vehicles. A recent study of parts sales and labor requirements for repair and maintenance of conventional cars revealed that 72 percent of labor hours and 62 percent of parts sales were required for the engine and its fuel, ignition, cooling, and exhaust systems, none of which are present in an electric car.[6] Although conventional car maintainability is expected to continue to improve, current estimates indicate that maintenance cost per mile for electric vehicles may be some 60 percent less than for conventional vehicles. This is partly because electric motors are extremely reliable, and normally require very little maintenance. Periodic brush replacement is generally all that is required, and this is only done every year or two. Electronic components such as choppers and chargers are constructed in a modular fashion and are normally replaced as whole units, often at higher cost.

The only other major electrical component is the propulsion battery pack. In an EHV powered by a lead-acid battery system, the sheer number of cells needed greatly increases the chances of experiencing at least one cell failure within the system, given current battery technology. This is critical because loss of one or more cells can severely affect battery performance and corresponding effective battery range. This potential problem is further compounded in advanced battery systems, such as zinc-chlorine and lithium-metal sulfide which are not modular, but simply consist of a "black box." Repair in these cases, unlike a lead-acid battery, requires more than the simple replacement of a particular defective cell or module; instead, the entire system, in some cases, must be removed and disassembled to effect the repair. To what extent improved technology can eliminate or reduce these potential reliability problems is unclear.

Although hybrid vehicles utilize an ICE in addition to the electric system, the ICE is used for as little as 20 percent of total annual vehicle mileage. As a result, hybrid maintenance costs should be substantially less than for a conventional vehicle, but greater than for an electric. This is because most failures are a function of miles driven and conditions under which driving occurs. Cold-start driving and short trips, as well as stop-start driving, are particularly hard on a conventional vehicle; they present little or no problem for range-extension hybrids, but may raise significant problems for high-performance hybrids.

The major disadvantage of EHVs that motorists would incur is high initial cost (Table 7.14). It is estimated that near-term EHVs may range from 60 to 80 percent higher in initial cost than conventional vehicles. In the case of advanced vehicles, EHVs may range from 20 to 40 percent higher on a first-cost basis. This is important because potential buyers tend to place a high premium on dollars invested initially in comparison to savings over the vehicle's life cycle. Unfortunately, higher initial cost is inherent in EHVs because batteries are more expensive than gasoline stored in a tank, and heavy batteries require a heavier, more expensive vehicle structure.

Overall life-cycle costs in general will also be higher, at least in the case of near-term vehicles (Table 7.14). Given current electricity and gasoline prices, near-term EHVs would range from 3 to 20 percent higher than conventional vehicles. Even with the near-term zinc-chlorine battery, the electric would cost more to own than a conventional vehicle over its entire life. In the case of the advanced batteries, however, EHVs could be from 8 to 11 percent cheaper. If the public becomes aware that life-cycle costs rather than initial costs represent the "bottom line," this could present a strong incentive to switch to EHVs.

The cost comparisons presented in Table 7.14 are all based on a gasoline price of $1.25 per gallon and an electricity price of 3 cents per kilowatt-hour. If gasoline prices rise relative to electricity, EHVs will become more cost-effective from a life-cycle standpoint.

If gasoline prices rise, but electricity prices remain constant (Fig. 7.8), all of the representative electric vehicles would have lower life-cycle costs than conventional vehicles at gasoline prices of $3 per gallon and above. In the case of hybrids, a price of $3.10 per gallon or higher would yield the same results. Although, from a realistic standpoint, electricity prices tend to follow a rise in the price of gasoline, they do tend to lag behind at first and then "catch up" later. This trend could create a large price differential much of the time.

Hybrids overcome the major disadvantage of electric vehicles, namely, limited range. This is particularly important in households having only one vehicle. However, advanced batteries are expected to provide EV ranges of 150 miles or more between recharges by the year 2000. This range would be adequate for 98 to 99 percent of all motorists in the largest urban areas on a given day, but it would suffice for no more than 90 percent of all miles driven on those days.

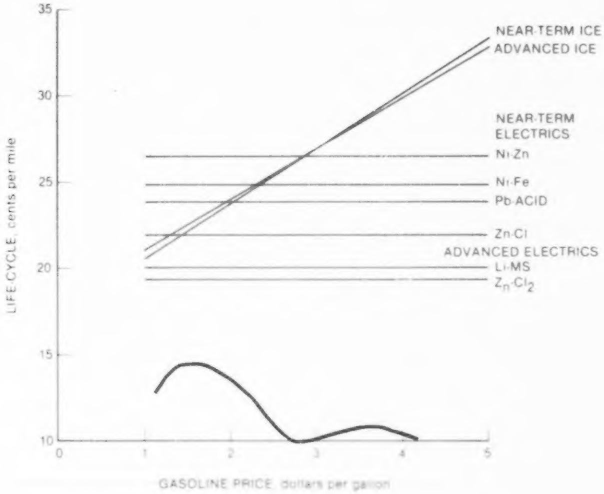
TABLE 7.14

COST COMPARISON OF ELECTRIC, HYBRID, AND CONVENTIONAL VEHICLES

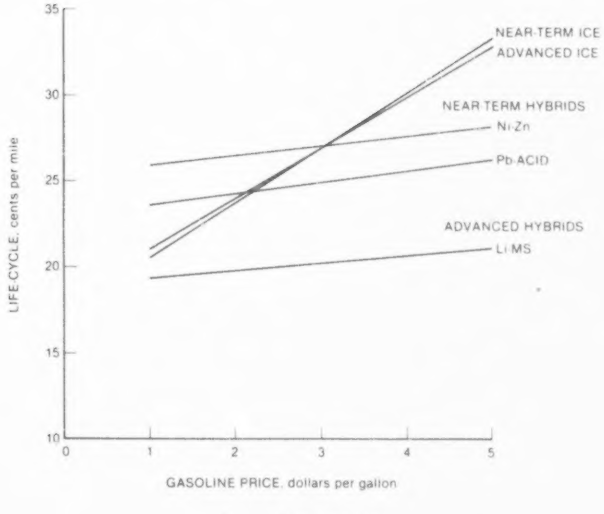
Vehicle	Initial Cost, 1980 dollars	Life-Cycle Cost, cents per mile
Electric		
Near-Term:		
Pb-Acid	8,520	23.9
Ni-Fe	8,400	24.9
Ni-Zn	8,130	26.6
$Zn-Cl_2$	8,120	22.0
Advanced:		
$Zn-Cl_2$	7,050	19.4
Li-MS	6,810	20.1
Hybrid		
Near-Term:		
Pb-Acid	8,020	23.7
Ni-Zn	7,770	26.0
Advanced:		
Li-MS	6,200	19.4
Conventional (ICE)		
Near-Term	4,740	21.4
Advanced	5,140	21.8

Source: Tables 3.5 and 4.2

Assumptions: These cost estimates were developed using a cost estimation model developed by General Research Corporation. The model used the EHV characteristics described in Sections 3 and 4 of this report as the basis for these estimates. Gasoline was assumed to cost $1.25 per gallon, and recharge electricity was assumed to be 3 cents per kilowatt-hour.



a. Electrics



b. Hybrids

Source: Tables 3.6 and 4.3

Assumption: The price of electricity was held constant at 3 cents per kilowatt-hour and the price of gasoline was varied from $1.00 to $5.00 per gallon.

Figure 7.8 Life-Cycle Costs of Electric, Hybrid, and Conventional Vehicles Versus Gasoline Prices

7.7 MAJOR UNCERTAINTIES

The major areas of uncertainty which must be considered in assessing the impacts of EHVs are the price and availability of hybrid fuels, improvements in battery technology, future sales of EHVs, growth of the electric utility industry, and improvements in conventional vehicles. History has demonstrated that projections of expected improvements in battery technology have tended to be overoptimistic. EHV sales are primarily uncertain because the future price and availability of petroleum fuels are unknown, and because consumers preference are uncertain. The electric utility industry is currently experiencing sharp declines in the growth rate of both electric generating capacity and electricity usage, making prediction of capability for recharging difficult. The extent to which the fuel economy of advanced conventional vehicles can be improved is also uncertain. If very fuel-efficient (60-100 mpg) vehicles become available, the market potential of EHVs could be sharply limited. Each of these major areas of uncertainty is discussed below.

7.7.1 Improvements in Battery Technology

It is clear that batteries are the key factor for practical EHVs. Electric motors and controllers are highly developed; they can be extremely quiet and reliable, and reasonably light and inexpensive. Since the beginning of the century, in contrast, it has been the batteries that have limited the range and speed of electric vehicles and kept them more expensive than automobiles with internal-combustion engines.

New kinds of batteries, however, offer prospects of greater improvements in the next decade than in the past eighty years. Improved lead-acid, nickel-iron, zinc-chlorine, and lithium-metal sulfide batteries are future possibilities which could double, triple, or even quadruple the amount of energy storage provided by the lead-acid "golf-cart" batteries now commonly used in electric cars. Developers of these batteries also expect operating life to increase as much as eight-fold, with corresponding reductions in life-cycle cost. Together, these improvements might dramatically relieve the principal disadvantages of electric drive.

Based on present progress and levels of effort projected for battery research and development, it seems likely that at least one of the battery types identified above will be successful. However, past performance clearly shows that battery development has usually not approached the expectations of developers. This may be due to the fact that it is so much easier to foresee a battery's potential performance than its implicit practical problems. The estimates presented here are intended to place reasonable upper and lower bounds on the prospects for future batteries.

7.7.2 Future Sales of EHVs

Under even the most optimistic battery projections, the success of EHVs in competing with conventional vehicles in the marketplace will depend primarily on the price and availability of gasoline relative to electricity. Price tags of EHVs will remain high despite major technological advances, due to the dominant cost of the batteries and, to a lesser extent, the fact that a heavier structure must be used to support these batteries. Although they would probably last longer than conventional vehicles because of the inherent longevity of their electric drive trains and are expected to require less maintenance and repair, large savings in fuel costs will be required to offset the extra initial costs of EHVs, particularly in the near term. The future price and availability of gasoline, however, cannot reliably be projected.

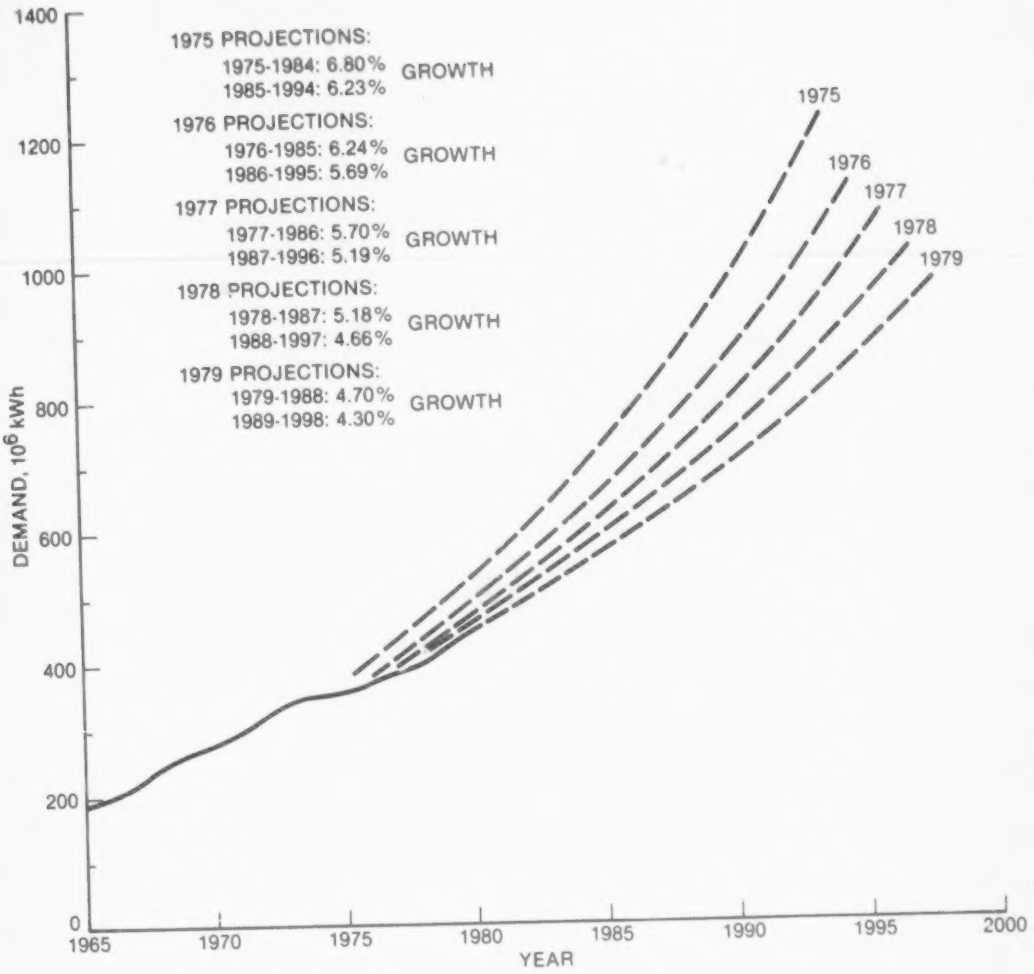
It is also uncertain whether buyers can readily adjust to vehicle range restrictions. Although we assume that travel patterns will remain the same, thus requiring EV owners to shift some travel to other vehicles or other modes of transportation, it is not clear whether this will actually occur. For example, rather than renting a conventional vehicle for trips beyond the effective range of an electric vehicle, an owner might simply prefer to forego many of these trips--and both the benefits and expenses.

7.7.3 Growth of the Electric Utility Industry

For many years, growth in the electric utility industry was remarkably predictable. With only minor variation from year to year, overall capacity and peak demand grew about 8 percent annually, doubling every eight to ten years. In the 1970s, however, this steady trend was interrupted. Although annual growth rates are highly dependent upon weather conditions, conservation measures, and the economic climate, it is estimated that the current average growth rate is from 3 to 4 percent per year.

Concerns for environmental quality and public safety have made it difficult or even impossible to obtain sites and construction permits for new power plants. Financing the huge expenditures needed to double capacity every ten years also has become a major problem. In the wake of the oil embargo of 1973-1974, the growth of demand dropped drastically, and utilities cancelled or postponed planned expansion accordingly. The national commitment to develop nuclear electric power faltered, future supplies of nuclear fuels began to appear uncertain, and public initiatives to restrict or prevent construction of nuclear power plants appeared in a number of states.

As a result, confident forecasting of supply and demand for electric power is no longer possible. Conditions have been changing too rapidly, and stability is not yet in sight. Since the 1973-1974 OPEC oil embargo, each new annual projection by the utility industry has embodied a lower rate of growth than in the previous year (Fig. 7.9). The difference in resultant projections made just two years apart is enormous: by 2000, it could be over twice the total peak demand actually recorded in 1970.



Source: Electric Power Supply and Demand for the Contiguous United States, Regional Electric Reliability Councils, US Department of Energy, 1 April 1975, 1976, 1977, 1978, 1979.

Figure 7.9 Recent Projections of Peak Summer Demand for Electric Power

On the supply side, there are uncertain prospects for making the transition to nuclear and coal-fired power plants to reduce petroleum consumption. Thus far it has been concluded that no additional power plants, other than those already planned for by the electric utility industry to meet normal future demand, would be needed to recharge EHVs if off-peak electricity is utilized. However, if the utilities are forced to build petroleum-fired power plants instead of nuclear and coal-fired plants, the fuel mix required to generate recharge energy would shift more toward petroleum, thus reducing the primary advantage of EHVs. If they cannot build replacement plants, then available capacity for generating recharge energy would be reduced.

This is a major area of uncertainty because the future status of conventional nuclear plants is doubtful, given the concerns of public safety, environmental protection, and the cost and availability of nuclear fuels. The question with coal is whether or not emission control technology can be improved enough to meet air quality standards without greatly increasing the price of electricity. The development of unconventional oil and gas in the synfuels program is in the early decision-making stages of development, and is also quite unclear. Although the industry could begin implementing new power plants which utilize more fuel-efficient equipment and retrofit some existing plants, these steps require substantial capital which is difficult to justify given demand that is down from earlier projections.

The prospects for transition to renewable resources such as solar and geothermal are even more unclear, as are the potentials of the advanced nuclear breeder reactor and fusion power. Furthermore, these sources are unlikely to have an effect until after the year 2010, rather than in the time frame considered in this report.

7.7.4 Improvements in Conventional Vehicles

In order to evaluate the utility of EHVs, it is necessary to make comparisons with those conventional vehicles that could provide the greatest competition for EHVs, namely, small urban cars. For the year 2010, it was assumed that the average new car could achieve a composite fuel economy of 55 miles per gallon, double the CAFE standard of 27.5 mpg for 1985. Light trucks were assumed to achieve about 37 miles per gallon. Since these are averages, some small cars and trucks would have higher fuel economy. However, there is great uncertainty as to whether these fuel economies will be required, attained, or surpassed.

On one side is the automobile industry, which has tended to resist external demands for rapid changes in technology. At the other is the Federal Government, which is currently striving to reduce petroleum consumption, with corresponding reductions in imports. Recent testimony before the Senate Committee on Energy and National Resources recommended that a target for Corporate Average Fuel Economy (CAFE) be set at 50 mpg for 1990, and 80 mpg for 1995.[16] Whether or not these targets could be achieved would depend largely on market characteristics and the associated incentives or disincentives. In any case, however, an average fuel economy of 50-80 mpg for new cars would entail major reductions in vehicle size, capacity, and performance, even with major improvements in automotive technology. If these levels of fuel economy are achieved by 1995, and continued to be improved upon, they would significantly reduce the primary advantage of EHVs, making them much less competitive.

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APPENDIX

ASSUMPTIONS FOR PROJECTING WEIGHT AND PERFORMANCE OF ELECTRIC AND HYBRID VEHICLES

Weight of an electric vehicle was estimated based on these assumptions:

1. Propulsion weight must be proportional to vehicle test weight (i.e., the curb weight plus payload during acceleration tests).

2. Structure and chassis weight must be proportional to gross vehicle weight (i.e., curb weight plus the maximum allowed payload).

3. Battery weight must be some arbitrary fraction of weight.

4. Upper body weight is given for a specified payload.

5. Vehicle curb weight is the sum of propulsion weight, structures and chassis weight, and upper body weight.

Table A.1 shows the combination of these assumptions into a parametric weight model. The key parameter here is battery fraction f, the fraction of vehicle test weight devoted to battery. Use of the model requires estimates for payload weight, upper body weight, the propulsion fraction a (the fraction of test weight devoted to the electric drive train), and the structure fraction b (the fraction of gross vehicle weight devoted to structure and chassis). These estimates are summarized in Table A.2.

The propulsion weight fraction a in Table A.2 is based on an overall requirement for capability to accelerate from 0 to 40 mph in 10 seconds. As discussed in Chapter 2, this suffices for safe entry into freeway traffic and requires an electric drive train output of about 28 hp per ton of vehicle test weight. This horsepower requirement, combined with the drive train weights and efficiencies of Table A.3, yields the propulsion weight parameters in Table A.2 for passenger cars. For light trucks, which historically employ transmissions and axles weighing more per horsepower of capacity, propulsion weight parameters in Table A.2 are correspondingly higher.

Range and energy use of electric vehicles were estimated using the ELVEC computer simulation. ELVEC was constructed in 1976 by General Research Corporation to support projections fo electric vehicle capabilities for a DOE study, and was subsequently expanded to support analyses for DOE of electric and hybrid vehicle performance standards. After a survey of over a hundred competing models and simulations, the

TABLE A.1

PARAMETRIC REPRESENTATION OF ELECTRIC VEHICLE WEIGHT

Symbol	Definition	Formula
$W_{PL,max}$	Maximum design payload	--
W_{UB}	Upper body weight	--
W_G	Gross vehicle weight	$W_G = W_C + W_{PL,max}$
W_C	Curb weight	See below
W_T	Test weight	$W_T = W_C + 300$ lb
W_S	Structure and chassis weight	$W_S = a \cdot W_G$
W_P	Propulsion weight	$W_P = b \cdot W_T$
W_B	Battery weight	$W_B = f \cdot W_T$

$$W_C = W_{UB} + W_S + W_P + W_B = \frac{W_{UB} + aW_{PL,max} + 300(b + f)}{1 - (a + b + f)}$$

Source: W. Hamilton, Electric Automobiles, McGraw-Hill Book Company, New York, 1980

TABLE A.2

WEIGHT PARAMETERS FOR ELECTRIC VEHICLES

Vehicles with Near-Term Batteries	Maximum Payload, lb	Upper Body Weight, lb	Structural Weight Fraction, a	Propulsion Weight Fraction, b
4-Passenger Car	900	833	0.247	0.101
5-Passenger Car	1200	957	0.243	0.101
6-Passenger Car	1650	1226	0.237	0.101
Compact Pickup	1190	882	0.241	0.109
Compact Van	1190	996	0.241	0.109
Vehicles with Advanced Batteries				
4-Passenger Cars	900	719	0.239	0.083
5-Passenger Cars	1200	826	0.237	0.083
6-Passenger Cars	1650	1056	0.232	0.083
Compact Pickup	1190	761	0.2363	0.091
Compact Van	1190	860	0.2363	0.091

Source: General Research Corporation

Cal Tech Jet Propulsion Laboratory (JPL) chose ELVEC in 1978 for continued development. JPL now maintains ELVEC for general use on a nationwide computer time-share system.

ELVEC used as inputs vehicle and battery weights from the model of Table A.1, propulsion efficiencies from Table A.3, and the road load parameters shown in Table A.4. It was run to determine range and energy use of electric vehicles with the batteries and battery fractions in Table A.5. Battery performance was described in Sec. 2.2; ELVEC outputs were summarized in Secs. 2.5 and 2.6.

TABLE A.3

SPECIFIC WEIGHTS AND EFFICIENCIES OF PROPULSION COMPONENTS

Technology	Component	Specific Weight, lb/hp	Average Efficiency, percent	
			City	Highway
Near-Term	Improved DC traction motor with transistor controller	6.25	82.5	87.5
Advanced	Brushless variable-reluctance "disc" motor with 3-phase semiconductor controller	4.93	85.0	90.0
Near-Term and Advanced	4-speed transmission, clutch, axle	0.93	94.0	96.0

Source: W. Hamilton, Electric Automobiles, McGraw-Hill Book Company, New York, 1980.

TABLE A.4

ROAD LOAD PARAMETERS FOR REPRESENTATIVE FUTURE VEHICLES

Rolling Resistance Coefficient: Near-Term - 1.18%
Advanced - 1.08%

Aerodynamic Drag Parameters:

Vehicle	Drag Coefficient	Frontal Area, ft^2
4-passenger car	0.35	20
5-passenger car	0.35	23
6-passenger car	0.35	26
Compact pickup	0.45	20
Compact van	0.40	30

Source: General Research Corporation

TABLE A.5

BATTERY FRACTIONS AND WEIGHTS FOR 4-PASSENGER ELECTRIC CARS

Near-Term Cars:							
	Battery Fraction	0.2	0.24	0.28	0.32	0.36	
	Battery Weight, lbs	567	746	964	1235	1580	
Advanced Cars:							
Zinc-Chlorine	Battery Fraction	0.1	0.15	0.2	0.25	0.3	0.35
	Battery Weight, lbs	201	330	486	678	922	1240
Lithium-Metal Sulfide	Battery Fraction	0.05	0.075	0.1	0.15	0.2	0.25
	Battery Weight, lbs	93	144	201	330	486	678

Hybrid cars were also analyzed using ELVEC and the assumptions tabulated here, slightly modified to allow for the addition of a small internal-combustion engine to the basic electric drive train. The engine was sized to provide the power requirement at 55 mph cruise (shown in Fig. A.1), plus a 25 percent reserve to overcome modest headwinds and grades without use of electric power, and to permit battery recharging during cruise to assure sufficient electric capability for occasional hills and bursts of acceleration. The near-term ICE was assumed to weigh 5 pounds per horsepower and to consume 0.6 pounds of gasoline per horsepower-hour. The fuel system was assumed to weigh 2 pounds per gallon of capacity, plus 6 pounds. For advanced ICE systems, these weights and the fuel consumption were reduced 10 percent. Hybrid vehicles were projected with the battery fractions and weights shown in Table A.6.

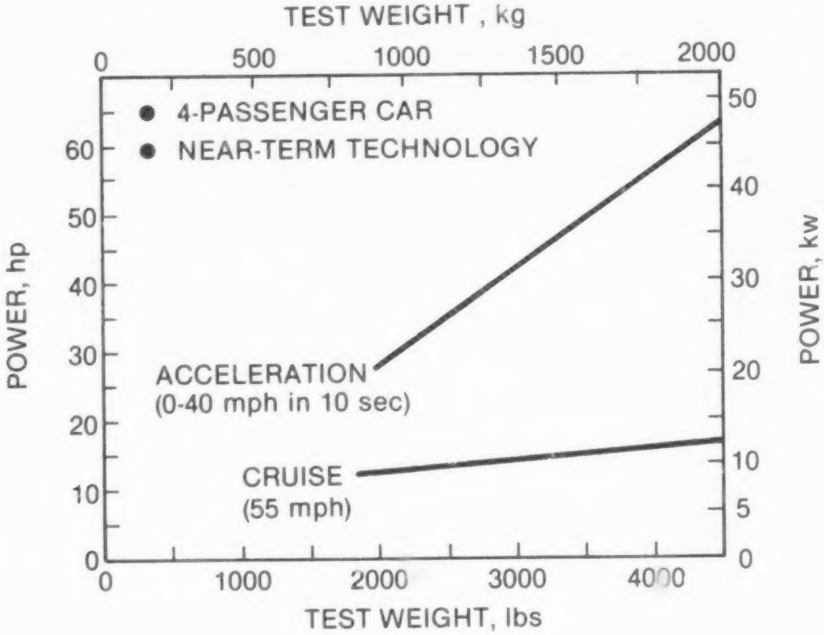

Figure A.1 Power Requirements for Acceleration and Cruise Versus Test Weight

TABLE A.6

BATTERY FRACTIONS AND WEIGHTS FOR FOUR-PASSENGER HYBRID CARS

Near-Term				
Battery Fraction	0.20	0.24	0.28	0.32
Battery Weight, lb	633	836	1086	1400
Advanced				
Battery Fraction	0.10	0.12	0.15	
Battery Weight, lb	221	275	364	

GLOSSARY

A-Weighted Sound Level. A system of measuring sound which emphasizes sounds in the middle frequencies to which the human ear is most responsive.

Advanced. A technology expected in this report to be commercially available by the year 2000.

Aerodynamic Drag. The force exerted by the air on a vehicle moving through it, opposing the motion of the vehicle.

Air Quality. A measure of the concentration of pollutants in the air.

Air Quality Control Regions (AQCR). A set of 248 regions, each covering an area of relatively homogeneous air quality, defined by the Environmental Protection Agency for planning purposes.

AQCR. Air Quality Control Region.

Armature. The movable part of a motor consisting essentially of coils of wire around an iron core.

Automotive Fuels. Liquids (or sometimes gases) which can be burned in internal combustion engines to provide enough energy to propel an automobile.

Available Capacity. The portion of the average electric power a generating unit is expected to be able to supply (after allowances for scheduled and unscheduled maintenance) which is not in use at a given time.

Baseline. The projected level of activity in the absence of electric and hybrid vehicles.

Base-Load Units. Those generating units of an electric power system which are intended to provide power continuously to the "base load" of the system (i.e., the load which is always present, even during the hours of minimum demand).

Battery. A group of cells in which an electrochemical reaction occurs, transferring ions between positive and negative electrodes through an electrolyte to produce an electric current.

Battery Charger. A device which feeds electricity into a battery, for storage in chemical form and later withdrawal as electric energy.

Battery Fraction. The ratio of propulsion battery weight to the test weight of an electric vehicle, indicating the fraction of the vehicle's on-road weight devoted to the battery.

Battery Weight. The weight of the propulsion battery or battery pack in an electric vehicle, including necessary interconnecting wiring between cells or other modules, supporting trays and any associated insulation and container required for battery operation.

Biberonnage. The practice of recharging electric or hybrid vehicle batteries in small amounts over short periods of time in various locations whenever the vehicle is parked away from home base.

Brushes. Electrical conductors made of blocks of carbon that make sliding contact between a stationary and a moving part of a motor.

CAFE. Corporate Average Fuel Economy.

Cartel. A coalition of independent commercial enterprises formed for the purpose of limiting competition, controlling supplies or regulating prices.

Cell. The basic unit of a battery consisting of a positive and a negative electrode connected by an electrolyte.

Chopper. A type of controller which periodically interrupts the flow of electric current to reduce its average value to the desired level.

Clean Air Act. Federal law passed in 1970 mandating air quality standards and limiting the amount of permissable pollutant emissions from various sources.

Commutator. A device which periodically reverses the direction of electric current in a motor as it revolves.

Continuous Duty Rating. The maximum power a motor car output continuously over a specified (extended) time period.

Controller. A device which regulates the amount of power flowing from the battery to the motor in an electric vehicle, thereby regulating the speed and acceleration.

Conventional Vehicles. Vehicles powered by Otto-cycle internal combustion engines using gasoline for fuel, using transmissions, tires, and materials typical of those used or confidently expected in 1980.

Corporate Average Fuel Economy (CAFE). The average miles per gallon attained by all the cars sold by a manufacturer which must meet federally mandated levels.

Curb Weight. The weight of a vehicle without driver, passengers or payload, but otherwise ready for operation.

Decibel. A unit for measuring the relative loudness of sounds; equal approximately to the smallest degree of difference of loudness ordinarily detectable by the human ear, whose range includes about 130 decibels on a scale beginning with one for the faintest audible sound.

Discharge. The withdrawal or depletion of electrical energy stored in a battery.

Dispatching Sequence. The order in which an electric utility uses the different fuels available to generate additional electric power.

DOE. The United States Department of Energy.

Drive Train. The components of a vehicle which convert stored energy into propulsive force, usually including an internal-combustion engine or electric motor and its controller, a transmission and a differential.

EHV. Electric and hybrid vehicles.

Electric Mode. The operation of a hybrid vehicle using only the electric storage battery as a power source.

Electric Vehicles (EVs). Vehicles whose propulsion power is electricity drawn from batteries.

Electricity Use of Electric Vehicles. The average electric energy input to the battery charger per mile of driving.

Electrification of Travel. The accomplishing of travel using electric vehicles, or hybrid vehicles operating on electricity alone, rather than conventional vehicles.

Electrode. Positive or negative plates in a battery which emit or accept ions during an electrochemical reaction.

Electrolyte. A non-metallic electric conductor in which current is carried by the movement of ions between the positive and negative electrodes in a battery.

Emissions. Substances released as a by-product of some activity.

Energy Efficiency. The percent of input energy which a device outputs after internal energy losses.

EV. Electric vehicle.

Federal Noise Control Act. A national policy established in 1972 to control the emissions of noise that are detrimental to human health.

Fleet Fuel Economy. The average miles per gallon attained by a group of vehicles.

Flywheel. A mechanical device for storing energy in a rotating wheel, usually made of high-strength metals or reinforced plastics and operated at high speed in an evacuated container.

Flywheel Hybrid. A vehicle which has incorporated into its propulsion system a flywheel to store and deliver energy.

Fossil Fuel. A carbon based burnable material composed of animal or plant matter which has decomposed in the earth's crust over the ages, such as oil or coal.

Friction Brakes. A device which slows the motion of a vehicle by mechanically applying friction to oppose the rotation of the wheels.

Fuel Economy. Miles traveled per gallon of fuel consumed.

Fuel Mix. The mix of fuels employed by electric utilities to generate electricity.

Gross Vehicle Weight. The weight of the vehicle plus the weight of maximum design payload.

HV. Hybrid vehicles.

Hybrid Vehicles (HVs). Vehicles equipped with two or more systems for supplying propulsion power such as vehicles with both a battery-powered electric motor and an internal combustion engine.

ICE. Internal combustion engine; a vehicle whose only propulsion power supply is an internal combustion engine.

Identified Resources. Specific bodies of mineral-bearing material whose location, quality and quantity are known from geologic evidence supported by engineering measurements.

Infrastructure. Basic institutions and facilities necessary for the continuance and growth of electric and hybrid vehicle use.

Initial Cost. Purchase price; the amount of money which must be expended to obtain the vehicle.

Internal Combustion Engine (ICE). A source of power (for propulsion of vehicles) in which power is supplied by piston movement caused by the controlled explosion of gasoline or other fuel.

Kilowatt (kW). The metric unit of power. It is 1000 times the work done in one second by a force which will impart an acceleration of one meter per second squared to a mass of one kilogram acting through a distance of one meter. In electrical circuits, power in kilowatts is given by the product of electromotive force and current (volts times amps) divided by 1000.

Kilowatt-Hour (kWh). The metric unit of energy. A kilowatt-hour is 3,600,000 times the work done by a force which will impart an acceleration of one meter per second squared to a mass of one kilogram acting through a distance of one meter.

Life-Cycle Cost. The expenditures required to purchase, operate, and maintain a vehicle throughout its useful life, including cost of capital.

Light-Duty Vehicles. Passenger automobiles and small vans and trucks with gross weight ratings under 10,000 pounds.

Long-Distance Travel. Generally inter-city travel of several hundred miles or more.

Market Penetration. The percent of all vehicles sold which are of a certain type.

Maximum Design Payload. The heaviest weight which a vehicle is designed to safely carry.

Median Automotive Passby Noise. Composite noise levels which average sound emissions during cruise and acceleration conditions representative of urban driving.

Motor. A rotating machine that transforms electrical energy into mechanical energy.

Near-Term. A technology expected in this report to be commercially available in quantity by the year 1990.

Noise Pollution. Unwanted sound which interferes with human activity.

Nominal Range. The mileage rating of a vehicle; the approximate distance which a vehicle will travel before refueling.

Off-Peak. A period of relatively low electricity demand as specified by the supplier.

Off-Peak Electricity Prices. A lower rate charged for electricity during periods of low demand.

Operating Cost. The cost of running and maintaining a vehicle throughout its life including charges for fuel, repair and maintenance, insurance, garaging, parking, tolls, titling, registration, replacement of parts with shorter lives than the basic vehicle and the cost of capital.

Operating Life. The period of time during which a device can function normally.

Outdoor Day-Night Equivalent Sound Level. Average community noise throughout a 24-hour day calculated by averaging the minute-to-minute readings of an A-weighted sound level meter, with nighttime readings increased 10 dB in recognition of the greater sensitivity of typical activities to noise during these hours.

Parallel Hybrid. A hybrid vehicle where the internal-combustion engine can drive the veicle by a direct mechanical linkage to the wheels.

Peak Demand. The maximum amount of electricity required during a specified time period, usually the hour of greatest demand during a calendar year.

Peaking Units. Those portions of a generating system used to supply electric power only during daily periods of maximum demand.

Pollutant. That which makes substances physically impure or unclean.

Population-Weighted Average. A regional average in which the importance of each sub-region's value is proportional to its population. The regional average is calculated by summing each sub-region value multiplied by the sub-region population, then dividing by the total regional population.

Potential Resources. Unspecified bodies of mineral-bearing material surmised to exist on the basis of broad geologic knowledge and theory.

Power. The time rate of transferring energy, equal to the current times the voltage in an electric circuit. The metric unit of power is the watt.

Power Plants. A location at which one or more electric power generating units are located.

Primary Demand. The demand for newly-mined material as opposed to scrap or recycled material.

Propulsion Weight. Total weight of the propulsion components in an electric, hybrid, or conventional vehicle, including propulsion battery, electric motor, controller, gasoline tank and fuel, internal combustion engine, transmission, and differential.

Range-Extension Hybrid. A hybrid-electric vehicle with sufficient speed and range on electric power alone for most driving, with a small internal-combustion engine which can be started after battery depletion on long trips to extend highway cruising range.

RECAPS. Recharge Capacity Projection System.

Recharge. To feed electricity into a battery to renew its ability to be used as an electric power source.

Recharge Capacity Projection System (RECAPS). A computer program which projects the capacity of US electric utilities to generate additional power for recharging EHVs, and the fuels which would be used to do it, based on existing and planned generating stations and the hour-by-hour electricity demand projected for an entire future year at each individual utility.

Recharge Electricity. Electricity fed into a battery to renew its ability to be used as a power source.

Recharge Energy. The amount of energy used in feeding electricity into a battery.

Recharger. A device which feeds electricity into a battery to restore its ability to supply electric power.

Recoverable Resources. That portion of the identified resource from which a useable mineral or energy commodity can be economically and legally extracted at the time of determination.

Regenerative Braking. A method of braking a moving vehicle in which the electric motor acts as a generator, allowing the kinetic energy of a vehicle during deceleration to be converted to electricity which recharges the battery, avoiding loss of that energy as heat in ordinary friction brakes.

Regional Emissions Projection System (REPS). A computer model which projects air pollution emissions by Air Quality Control Region.

REPS. Regional Emissions Projection System.

Resources. A concentration of naturally occurring solid, liquid or gaseous materials in or on the earth's crust in such a form that economic extraction of a commodity is currently or potentially feasible.

Road Load. The amount of force which must be applied to a vehicle to overcome the aerodynamic drag, rolling resistance, gravity and inertia. The total resistance to forward motion of a vehicle due to rolling resistance, aerodynamic drag, gravity (on inclined roadways), and inertia (during acceleration), which must be overcome by propulsive forces.

Rolling Resistance. The amount of force which must be applied to the vehicle to overcome the forces of friction in the tires and wheel bearings.

SEAS. Strategic Environmental Assessment System.

Selective Load Control. Remote control of selected classes of electrical equipment or appliances, exercised by a utility to reduce total demand and thus avoid blackouts when available generating capacity is inadequate; ordinarily applied briefly to non-critical devices such as electric hot water heaters or air conditioners, at households agreeing to such interruptions in exchange for reduced electricity rates.

Series Hybrid. A hybrid vehicle in which the engine drives a generator which in turn drives the electric motor or charges the battery.

Specific Cost. Cost per unit weight measured in dollars per kilogram.

Specific Energy. Energy per unit weight.

Specific Power. Power per unit weight.

Sticker Price. Suggested retail price.

Strategic Environmental Assessment System (SEAS). A computer model developed by the US Environmental Protection Agency to assess the impact of various environment-related policies on the economy and the environment, both in terms of dollar changes in gross national product and pollutant tonnages released into the biosphere.

Structure and Chassis Weight. The weight of the structure, suspension, tires, wheels, and other components which must carry the weight of the upper body, battery, propulsion system and payload.

Surface Transportation Vehicle. Any vehicle capable of carrying people or loads which moves across the ground.

Test Weight. The curb weight of a vehicle, plus a payload of plus 300 pounds (the conventional assumption for the weight of two average occupants).

Thermal Pollution. The introduction of hotter or colder elements into a substance causing an unwanted change in the substance's normal temperature.

Upper Body Weight. Weight of the passenger compartment, seats, instruments, heating and ventilation, and body panels.

Urban Driving Range. The distance a vehicle travels between refuelings or recharges in stop/start city traffic; usually tested in a specific driving schedule chosen to be representative of urban driving conditions.

Windings. Material, such as wire, wound or coiled about an object, such as an armature in a motor.

Office of Technology Assessment

The Office of Technology Assessment (OTA) was created in 1972 as an advisory arm of Congress. OTA's basic function is to help legislative policymakers anticipate and plan for the consequences of technological changes and to examine the many ways, expected and unexpected, in which technology affects people's lives. The assessment of technology calls for exploration of the physical, biological, economic, social, and political impacts which can result from applications of scientific knowledge. OTA provides Congress with independent and timely information about the potential effects—both beneficial and harmful—of technological applications.

Requests for studies are made by chairmen of standing committees of the House of Representatives or Senate; by the Technology Assessment Board, the governing body of OTA; or by the Director of OTA in consultation with the Board.

The Technology Assessment Board is composed of six members of the House, six members of the Senate, and the OTA Director, who is a nonvoting member.

OTA currently has studies underway in nine general areas: energy, international security and commerce, materials, food and renewable resources, health, human resources, communication and information technologies, oceans and environment, and space technology.

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